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To: NASA/Lyndon B. Johnson Space Center
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Enclosure: (1) Design Note No. 1.4-9-01, "Parametric Study Of Predictor Accuracy Impact On OFT Rendezvous Targeting."

1. The enclosed design note presents the results of a study performed to evaluate the effect of on-orbit predictor errors on OFT rendezvous targeting. The data presented may be used to establish requirements for the on-orbit predictor.

Very truly yours,

W. E. Hayes

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MCDONNELL DOUGLAS TECHNICAL SERVICES CO.
HOUSTON ASTRONAUTICS DIVISION

SPACE SHUTTLE ENGINEERING AND OPERATIONS SUPPORT

DESIGN NOTE NO. 1.4-9-01

PARAMETRIC STUDY OF PREDICTOR ACCURACY IMPACT ON OFT RENDEZVOUS TARGETING

MISSION PLANNING, MISSION ANALYSIS, AND SOFTWARE FORMULATION

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8 OCTOBER 1976

This Design Note is Submitted to NASA Under Task Order No. D0511, Task Assignment 1.4-9-D in Fulfillment of Contract NAS9-14960.

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1.0 SUMMARY

A parametric study was made to quantitatively define the effects of errors in the state vector predictor used by the OFT rendezvous targeting algorithms. The effect of the predictor accuracy on the OFT rendezvous profile is shown by the sensitivity of various critical rendezvous parameters (e.g., differential altitude at NSR, elevation angle at TPI) with respect to downrange and radial predictor error rates.

The effect of both inertial (same errors on both vehicles) and relative (differential errors on one vehicle with respect to the other) errors were considered. Relative radial error rates had the largest impact on the rendezvous followed by relative downrange errors, radial inertial errors and downrange inertial errors.

2.0 INTRODUCTION

The OFT rendezvous targeting onboard software will be required to target a four burn sequence which will cause the orbiter to leave a target and return on a relative motion profile similar to that used on Apollo and Skylab and expected to be used on the Shuttle operational ground-up rendezvous. The targeting algorithms require the use of a state vector predictor and the accuracy of targeted burns is dependent on the accuracy of this predictor.

The Command Module Computer targeting routines for Apollo and Skylab utilized both conic and Encke predictor formulations. Analysis and actual performance verified the adequacy of this scheme.

The predictor which shall be used by the Shuttle targeting algorithms must meet a variety of constraints. Computer resource (storage and timing) constraints require that the predictor be designed in an optimum manner such that unneeded accuracy is eliminated to reduce resource requirements. However, larger drag and venting effects may require a more extensive predictor than those which were adequate in the past.

This study was undertaken to establish specifications, independent of specific predictor techniques, which the predictor must meet. To accomplish this result, a specifically defined predictor error model was used by the targeting logic. The effect on rendezvous parameters of various predictor error magnitudes was tabulated and the results are presented.

3.0 DISCUSSION

The purpose of this study is to provide information necessary to determine the accuracy which will be required by the predictor used in the rendezvous targeting software. This information will be provided in the form of rendezvous sensitivities to predictor errors. In order to establish predictor specifications which are independent of actual predictor techniques, the approach employs a relatively simple predictor as a "truth model" to establish a reference trajectory and a precisely defined error is added to the "truth model" to determine the effects of the error on the trajectory. This technique assumes that the differences between the actual trajectory and the predictor used onboard will result in the same sensitivities.

The OFT trajectory was targeted with and without errors. The variation in critical parameters (Total ΔV, Range at TPF, etc.) were tabulated and the sensitivities in these parameters are presented in Sections 4 and 5.

3.1 Error Model

The error model developed for this study was capable of adding downrange and radial inertial (non-rotating) errors to the conic ("truth model") predicted state at regular steps through the prediction interval. A step size was chosen such that these errors appeared to be continuous (i.e., adding the errors at smaller steps had negligible effect). The errors were added negatively when the prediction interval was to a previous time and thus, due to the continuous nature of the error, the predictor would return a vector to its original position when the time was reversed.

Figures 1 and 2 indicate the effect of the inertial downrange and radial error rates, respectively. These plots indicate the difference between the actual ("truth model") predictor and the errored predictor in curvilinear rotating position and velocity as a function of time. The effect of a negative error rate would be to reverse the plots symmetrically about the time axis.

Note that a positive inertial downrange error rate results in a negative curvilinear rotating downrange position error (Figure 1, top left). This is because a downrange inertial position error produces a radially upward velocity in the curvilinear rotating frame, placing the error model position in a higher orbit than the actual position, and resulting in a fall back situation. The motion of the predicted position about the actual position in curvilinear rotating coordinates is shown in Figure 3 for both downrange and radial error rates. From the top chart of Figure 3, it can be seen that the positive downrange error rate initially produces a positive downrange curvilinear rotating error, but the radially upward motion produced soon causes a negative downrange error which increases with time.

The result of an inertial radial error rate on the curvilinear rotating radial position (Figure 2, top right) is essentially linear. The cyclic variation is because the inertial radial error causes a small downrange velocity error, which then feeds back into a radial position error, as described in the paragraph above.

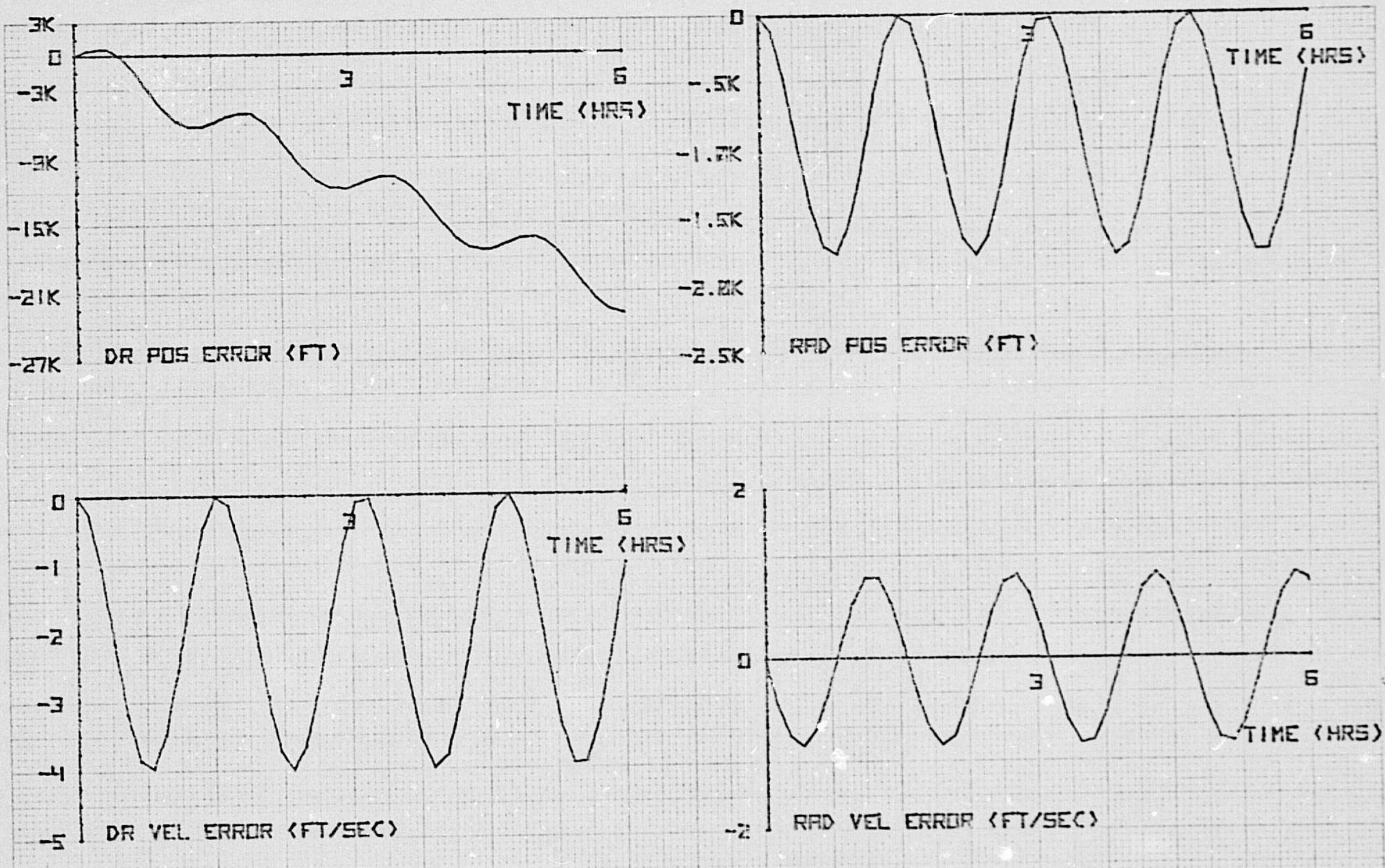


FIGURE 1 - EFFECT OF UNIT (+1 FT/SEC) INERTIAL DOWNRANGE
ERROR RATE IN ROTATING CURVILINEAR COORDINATES

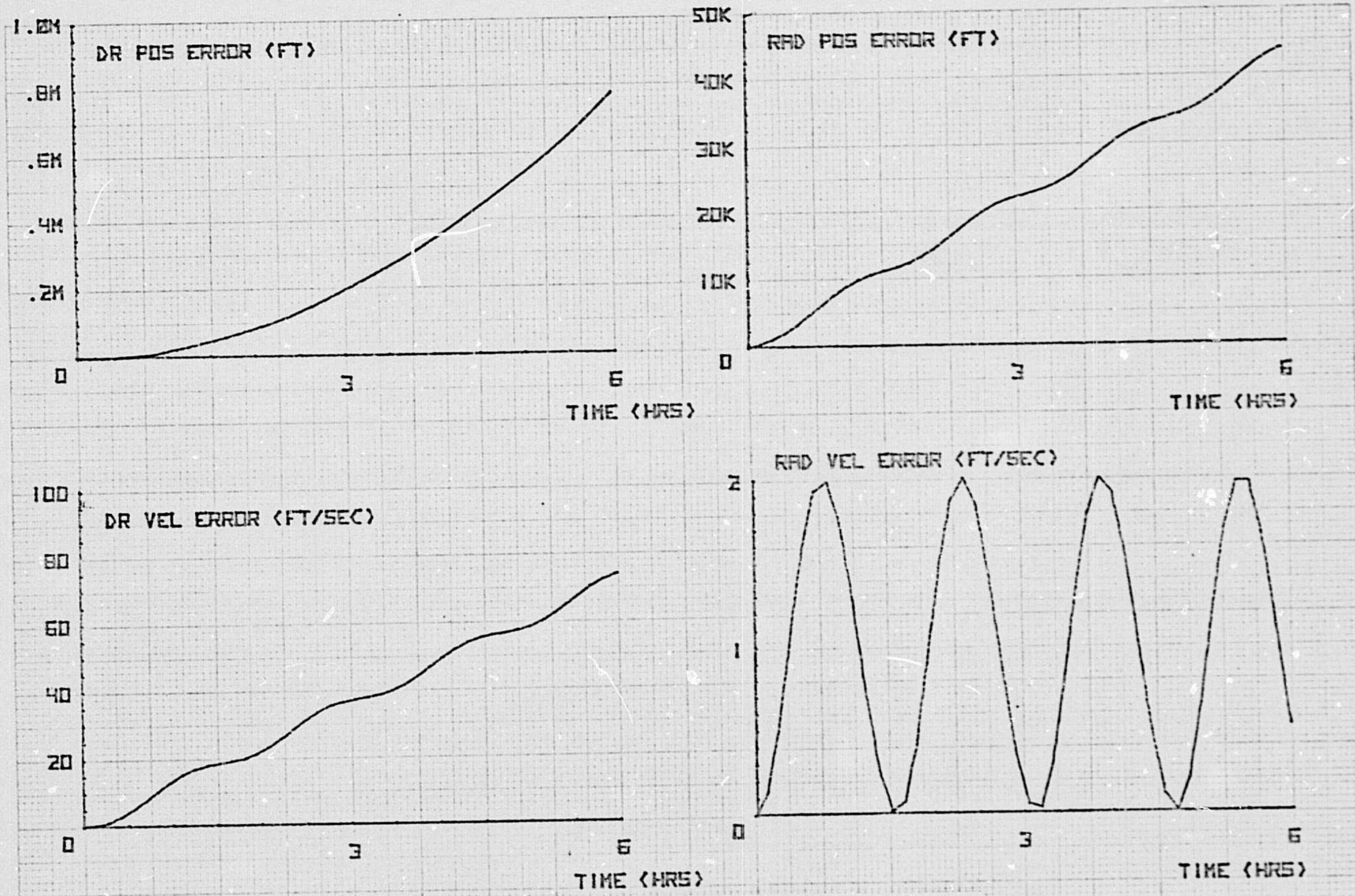
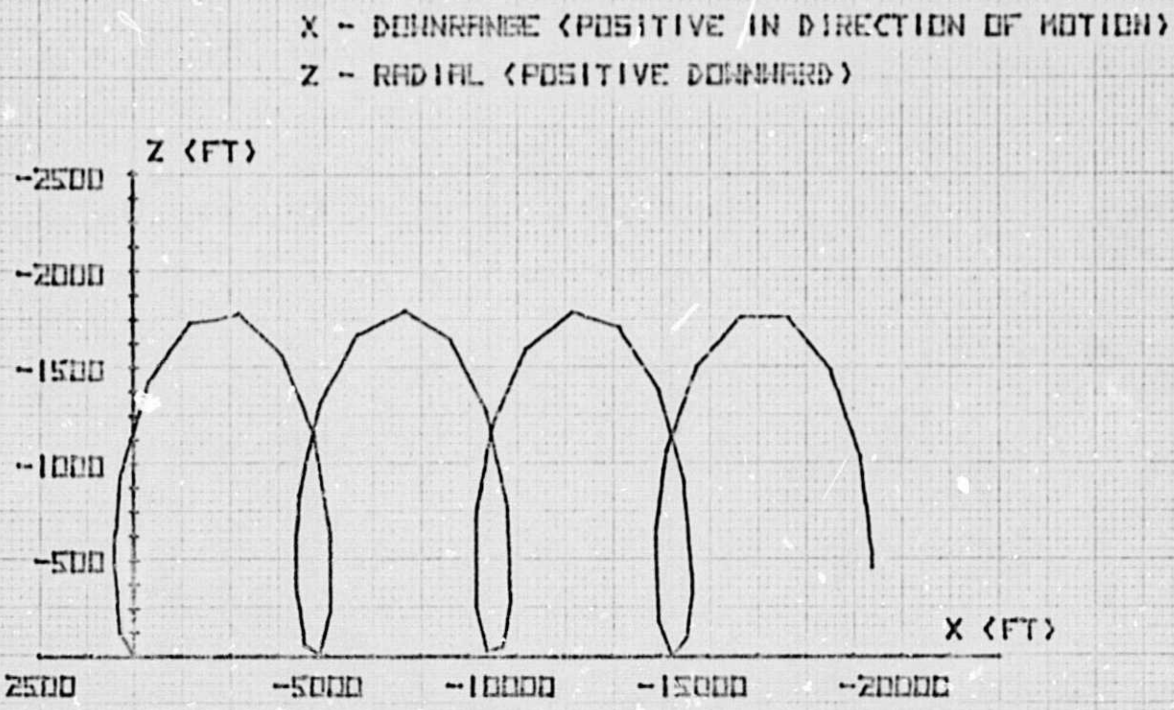
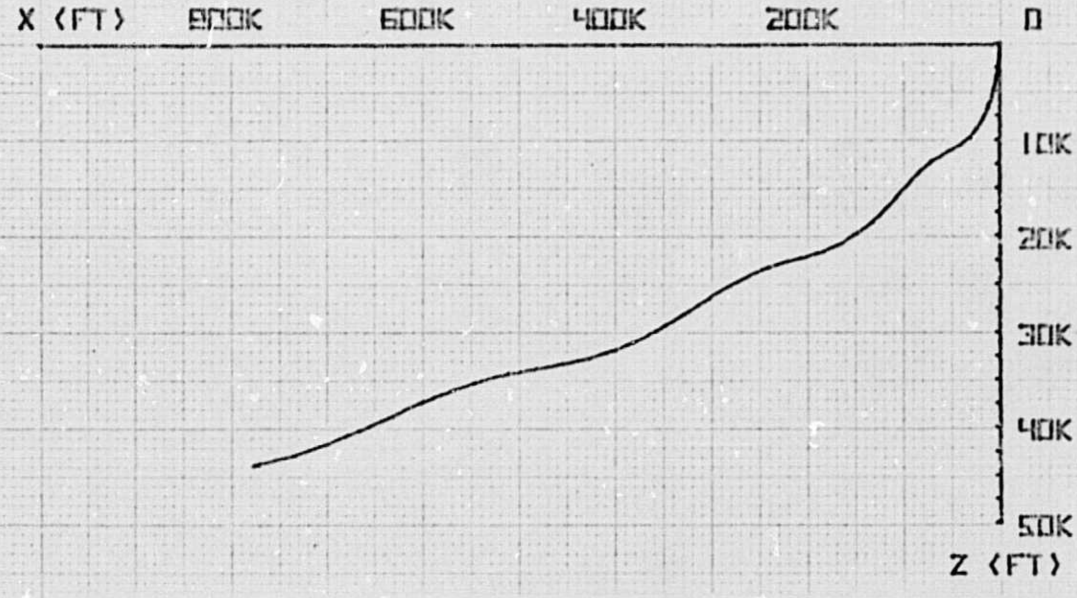


FIGURE 2 - EFFECT OF UNIT (+1 FT/SEC) INERTIAL RADIAL ERROR RATE IN ROTATING CURVILINEAR COORDINATES



DEVIATION RESULTING FROM 1 FT/SEC DOWNRANGE ERROR RATE



DEVIATION RESULTING FROM 1 FT/SEC RADIAL ERROR RATE

FIGURE 3 - POSITIONAL DEVIATION OF CONSTANT ERROR RATE PREDICTOR

The downrange position error due to an inertial radial error rate (Figure 2, top left) is approximately quadratic. This is the result of a downrange velocity error (Figure 2, bottom left) which is approximately linear because the predicted position is going into lower orbits at a constant (approximately) rate.

The effect of inertial error rates are proportional and additive (i.e., the effect on curvilinear rotating position shown in Figures 1 and 2 for 1 ft/sec error rates would be doubled for 2 ft/sec error rates and the effect of a combination of downrange and inertial error rates would be the sum of the effects of the downrange and radial error rates taken separately). Therefore, if the cyclical variation shown in Figures 1 and 2 is ignored, the relation between inertial error rates and curvilinear position error may be expressed as

$$DR_{CURV} = -\dot{\varepsilon}_{DR}\, T + .0016862\, \dot{\varepsilon}_{RAD}\, T^2$$

$$RAD_{CURV} = -900\, \dot{\varepsilon}_{DR} + 2\, \dot{\varepsilon}_{RAD}\, T$$

where DR_{CURV} and RAD_{CURV} are the curvilinear downrange and radial position errors, respectively, in feet; $\dot{\varepsilon}_{DR}$ and $\dot{\varepsilon}_{RAD}$ are the inertial downrange and radial error rates, respectively, in ft/sec; and T is the time over which the errors propagate in seconds.

3.2 Rendezvous Trajectory

The trajectory used for this analysis is shown in Figure 4. This trajectory represents the planned OFT trajectory which involves the separation from a target released earlier and a rendezvous back to it. The altitude of the target vehicle in this analysis was 250 NM.

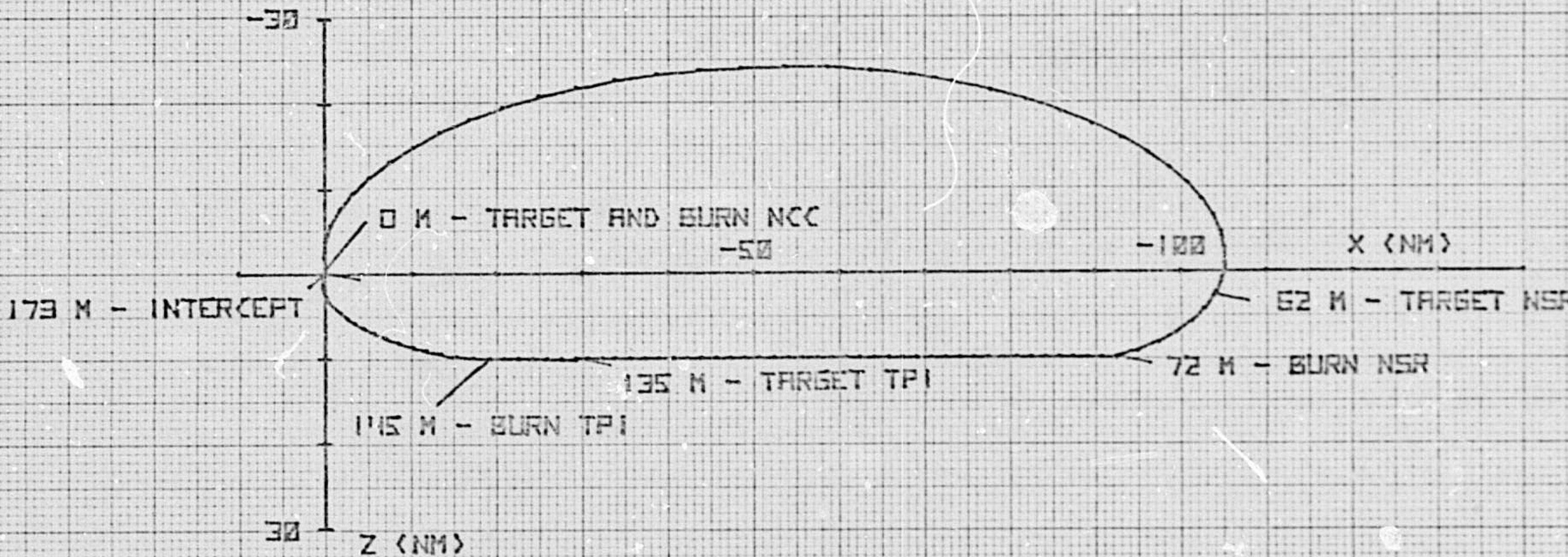


FIGURE 4 - ANALYSIS TRAJECTORY

The NCC burn in this analysis was targeted and burned at the same time ($t = 0$). No separation maneuvers were performed; both vehicles were at the same point at NCC. The other burns (NSR, TPI) were targeted ten minutes prior to nominal burn time. The NCC burn was targeted such that 1) NSR would occur 72 minutes after NCC, 2) NSR would be at a differential altitude of 10 NM, and 3) the TPI elevation angle of 27° would occur at $t = 145$ minutes. The TPI burn was constrained to be performed at the nominal time, no matter what elevation angle was actually obtained. The timeline for this rendezvous is summarized in Figure 5.

TIME	RELATIVE POSITION OF THE ORBITER	EVENT
0	AT TARGET (CIRCULAR ORBIT AT 250 NM ALTITUDE)	TARGET NCC TO DH_{NSR} = 10 NM, E_{TPI} = 27° BURN NCC (22.2, 0., -110.3)*
62 MIN	103.9 NM BEHIND 2.8 NM BELOW	TARGET NSR FOR T = 72 MIN
72 MIN	92.5 NM BEHIND 10.0 NM BELOW	BURN NSR (-56.1, 0., -39.9)*
135 MIN	29.3 NM BEHIND 10.0 NM BELOW	TARGET TPI FOR T = 145 MIN, $\omega\Delta T$ = 130°
145 MIN	19.3 NM BEHIND 10.0 NM BELOW	BURN TPI (18.3, 0., -9.6)*
179 MIN	AT TARGET	INTERCEPT (15.5, 0., 21.7)*

* Delta V shown is nominal burn in local vertical coordinates (X - downrange, Y - out-of-plane, Z - radial downward)

FIGURE 5 - ANALYSIS TRAJECTORY TIMELINE

3.3 Analysis Technique

The Interactive Orbital Maneuver Program which utilizes the targeting routines in the Space Vehicle Dynamics Simulation (SVDS) Program was used to target burns and perform the rendezvous as described in 3.2. However, when the targeting routines required the state predictor, the predictor error model was called.

The predictor error model had four options which determined which vehicle the errors would be added to:

1. No errors added to either vehicle - for reference run
2. Errors added to orbiter state only
3. Errors added to target state only
4. Errors added to both states

By utilizing the options of the predictor error model, two types of errors could be examined: inertial and relative. The inertial errors were determined by adding errors at the same rate to both vehicles when the rendezvous targeting required them to be predicted. It was expected that these errors would have a small effect on the rendezvous. Relative errors in prediction were determined by using an option which added errors to only one vehicle and the other was predicted without errors. It was expected that a relative error on one vehicle would produce the same effect as an error of opposite sign on the other vehicle. Results were obtained by performing a rendezvous for each combination of columns in Figure 6.

1. PREDICTOR ERROR ON	2. DIRECTION OF INERTIAL ERROR	3. MAGNITUDE OF PREDICTOR ERROR RATE IN	
		FT/HR	FT/SEC
BOTH VEHICLES (INERTIAL)	DOWNRANGE	-50000	-13.89
		-20000	-5.56
	RADIAL	-10000	-2.78
ORBITER (RELATIVE)		-5000	-1.39
		-2000	-.56
		-1000	-.28
TARGET (RELATIVE)		0	0
		1000	.28
		2000	.56
		5000	1.39
		10000	2.78
		20000	5.56
		50000	13.89

FIGURE 6 - RENDEZVOUS SIMULATION ANALYSIS CASES PERFORMED

4.0 RESULTS

The results of making the runs described in 3.3 confirmed the expectation that errors on one vehicle had the effect of errors of the opposite sign on the other vehicle. This effect is demonstrated in Figures 7 and 8 which compare the effect of orbiter and target errors on the total ΔV for both downrange and radial error rates. Figures 9 and 10 offer a similar comparison of the effect on TPI elevation angle. It can be seen from these comparisons that the target error effect is essentially the same as an orbiter error of opposite sign. Therefore, further presentation of target error data will not be required.

The effect of errors on the rendezvous was determined by examining the following parameters:

1) DH at NSR - Differential altitude of the orbiter with respect to the target at NSR burn time. Deviations from the nominal 10 NM are due to errors in targeting NCC.
2) Elevation Angle at TPI - Since TPI is performed at the nominal time, trajectory errors due to previous targeting errors result in TPI being performed at other than the nominal 27°. Deviations from the nominal are primarily due to errors at NCC.
3) Range at TPF - This range represents the distance from the target at the end of the rendezvous sequence. However, it is not necessarily the closest approach distance as the range may still be closing at TPF time. Range at TPF is a measure of the TPI burn accuracy.
4) DV Total - Total ΔV required to complete the rendezvous sequence. This includes the magnitudes of targeted velocities of the NCC, NSR, and TPI burns, as well as the actual ΔV required to go coelliptic

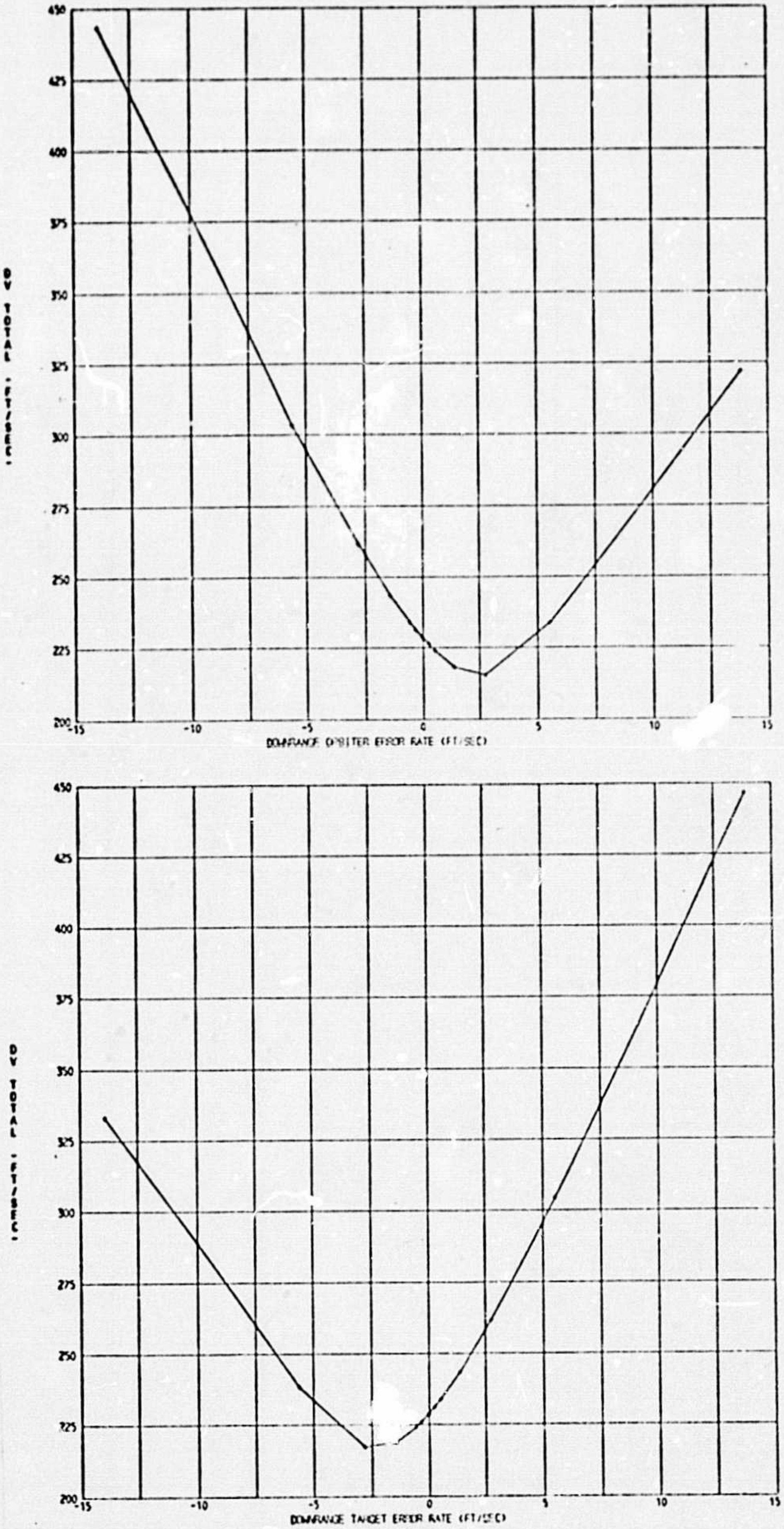
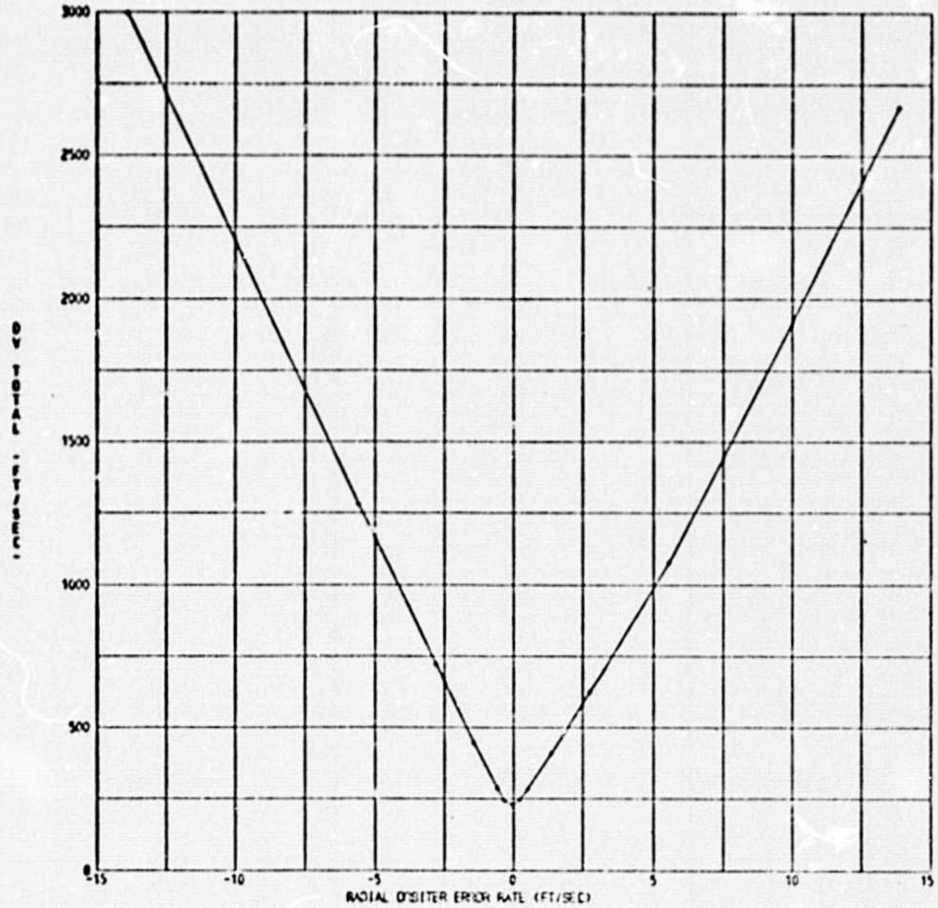


FIGURE 7 - EFFECT OF RELATIVE (ORBITER AND TARGET) DOWNRANGE ERRORS ON TOTAL DELTA V



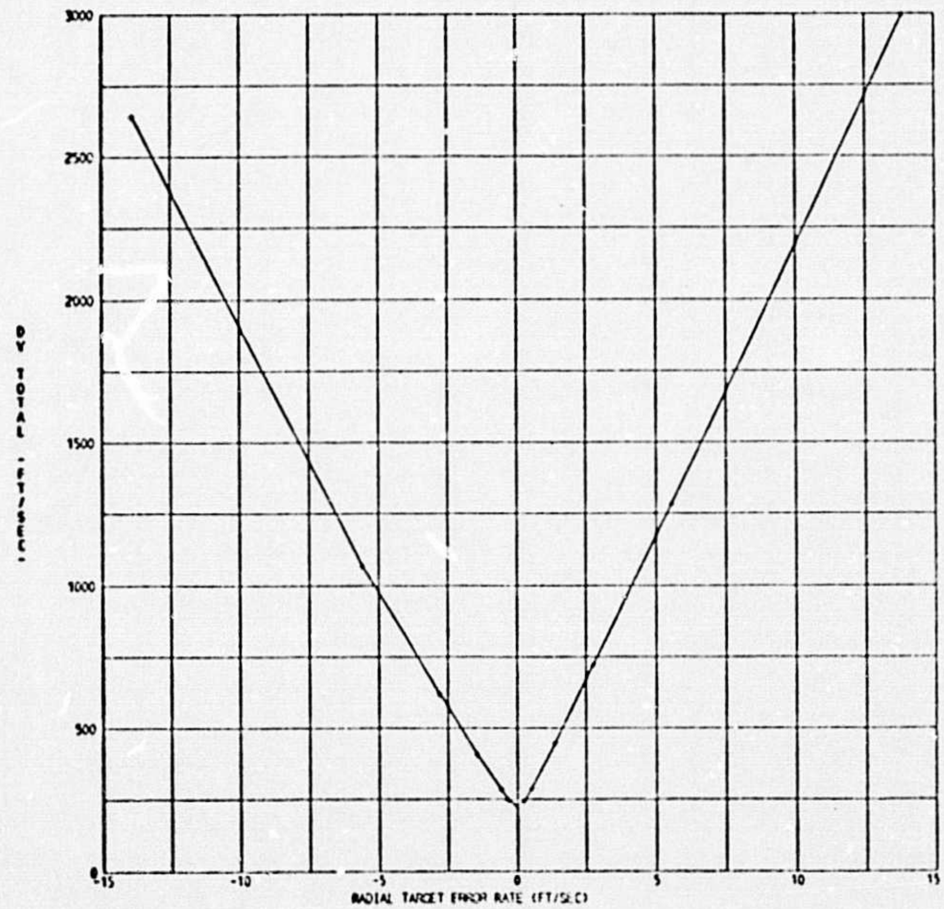
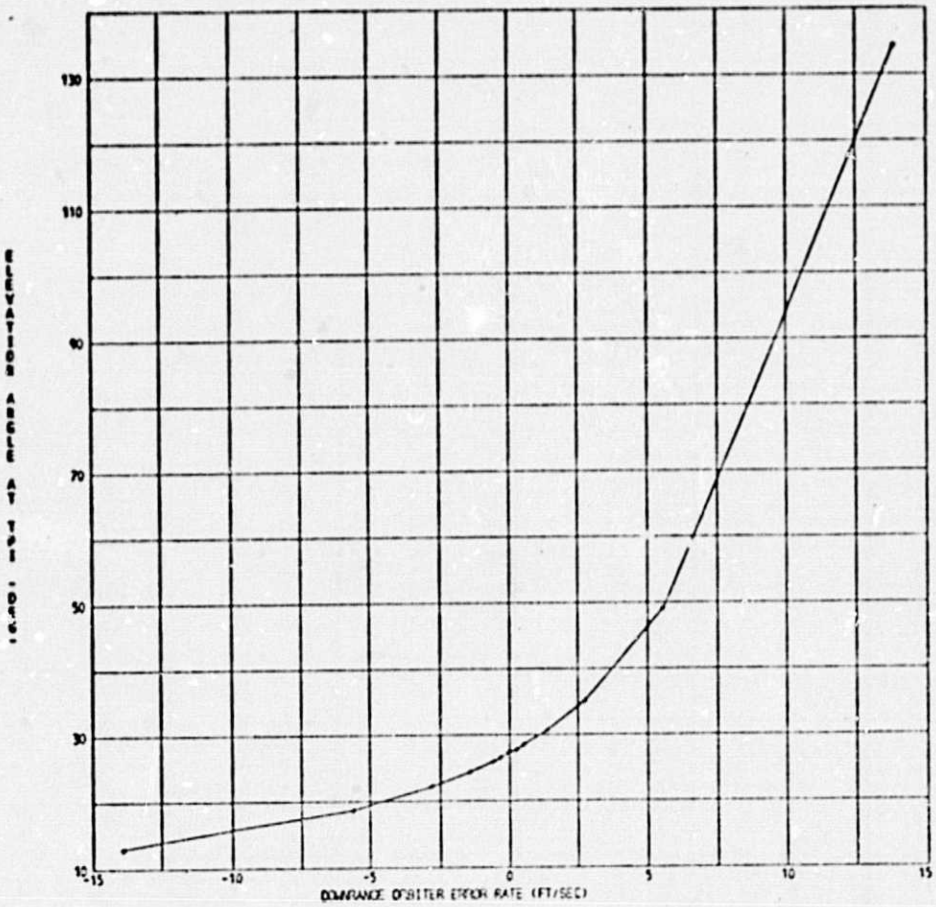


FIGURE 8 - EFFECT OF RELATIVE (ORBITER AND TARGET) RADIAL ERRORS ON TOTAL DELTA V



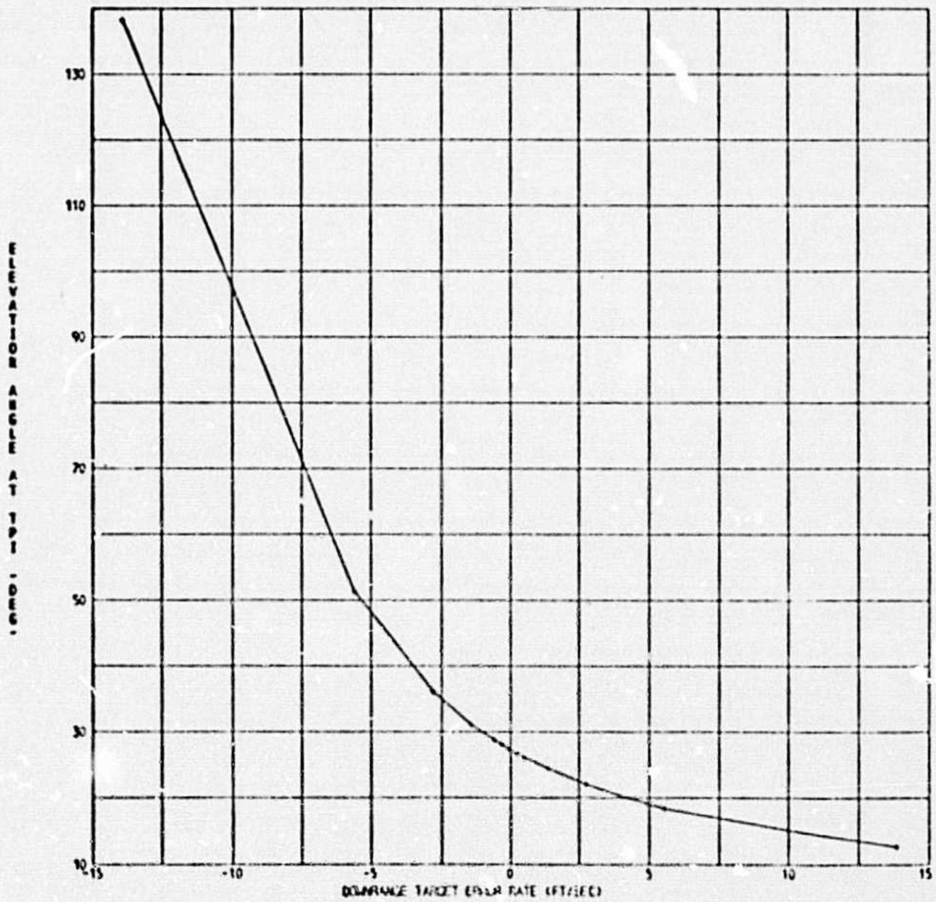
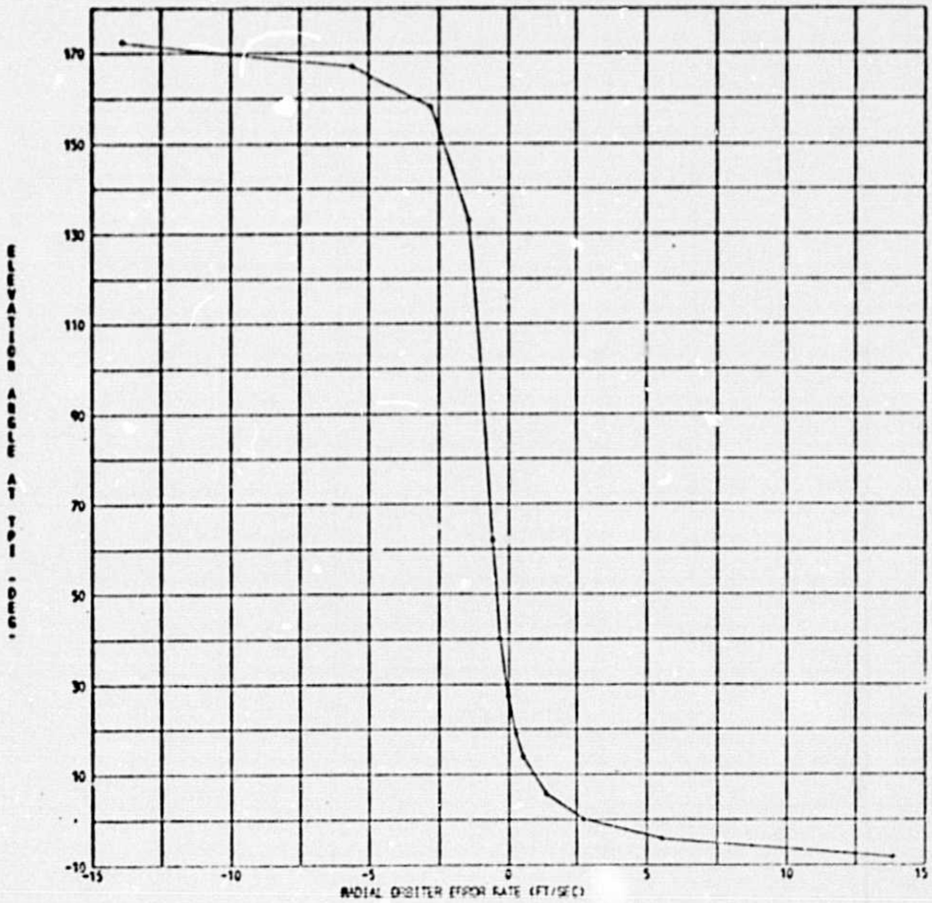


FIGURE 9 - EFFECT OF RELATIVE (ORBITER AND TARGET) DOWNRANGE ERRORS ON TPI ELEVATION ANGLE



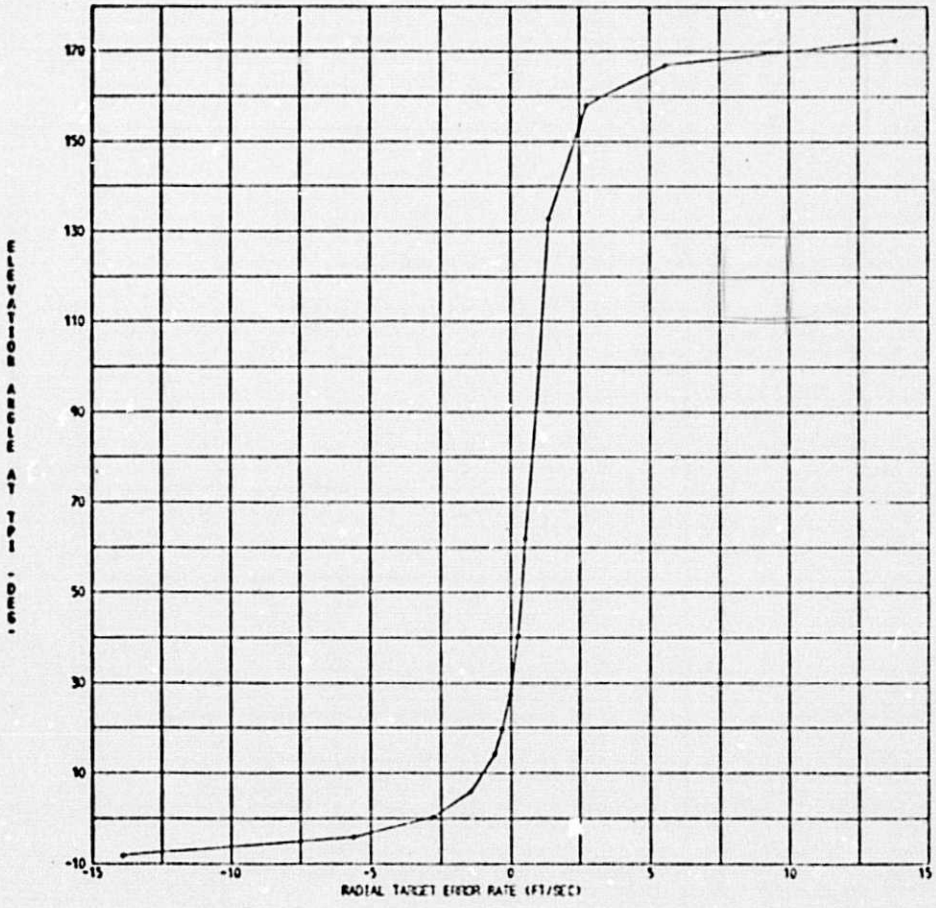


FIGURE 10 - EFFECT OF RELATIVE (ORBITER AND TARGET) RADIAL ERRORS ON TPI ELEVATION ANGLE

at TPF time:

$$DV_{TOTAL} = DV_{NCC} + DV_{NSR} + DV_{TPI} + DV_{TPF(ACTUAL)}.$$

Note that DV_{TOTAL} does not necessarily result in rendezvous with the target. Since errors will be included when TPI is targeted, the final trajectory may not be an intercept.

5) DV_{NCC} - Targeting of the NCC burn is the most sensitive to predictor accuracy because the predictor is used over the longest period of time. The NCC burn is most critical for determining the proper geometry at NSR and TPI.

6) DV_{NSR} - The NSR burn is least sensitive to predictor error because it only computes the coelliptic velocity. Note that a deviation from nominal does not necessarily represent an error, but may be an attempt to go coelliptic at a differential altitude other than 10 NM due to an NCC error.

7) DV_{TPI} - The TPI burn is sensitive to predictor errors, however, large deviations from nominal also represent additional ΔV required to correct a highly off-nominal trajectory.

Figures 11 through 18 indicate the effect of inertial downrange and radial errors on the parameters just described. Figures 19 through 26 present the variation in these parameters as a function of relative (orbiter only) errors.

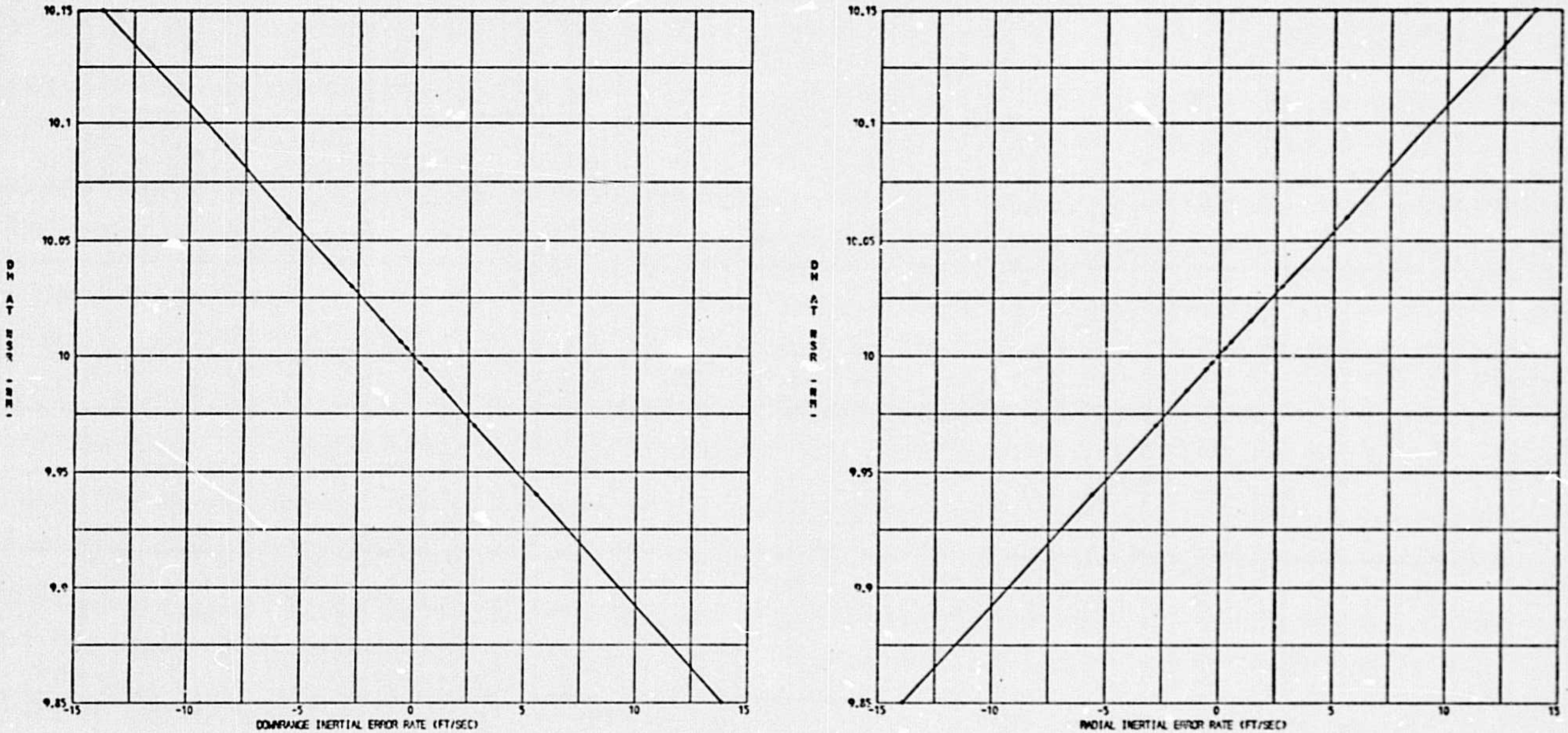


FIGURE 11 - DIFFERENTIAL ALTITUDE AT NSR DEPENDENCE ON INERTIAL ERROR RATE

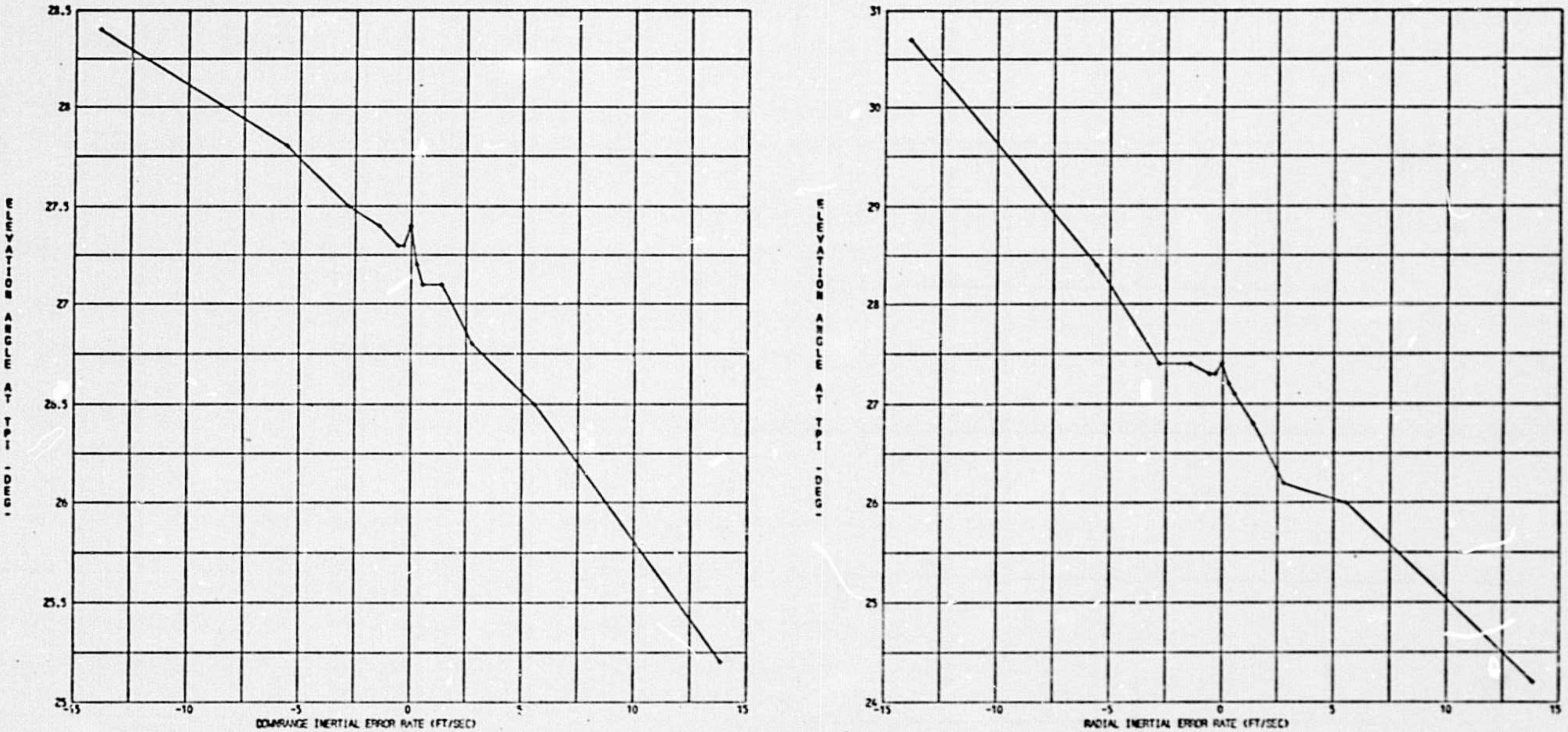


FIGURE 12 - TPI ELEVATION ANGLE DEPENDENCE ON INERTIAL ERROR RATE

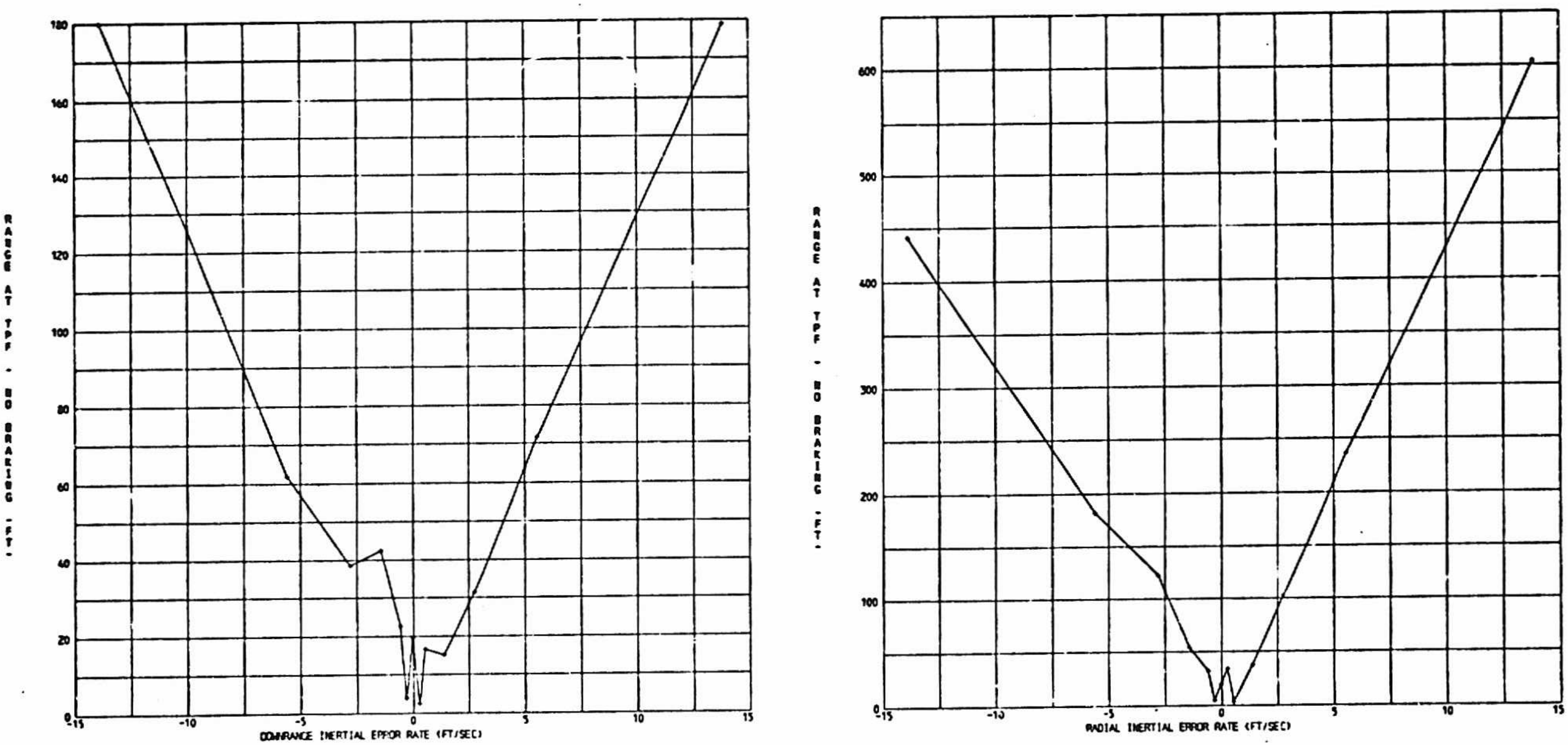


FIGURE 13 - RANGE AT TPF DEPENDENCE ON INERTIAL ERROR RATE

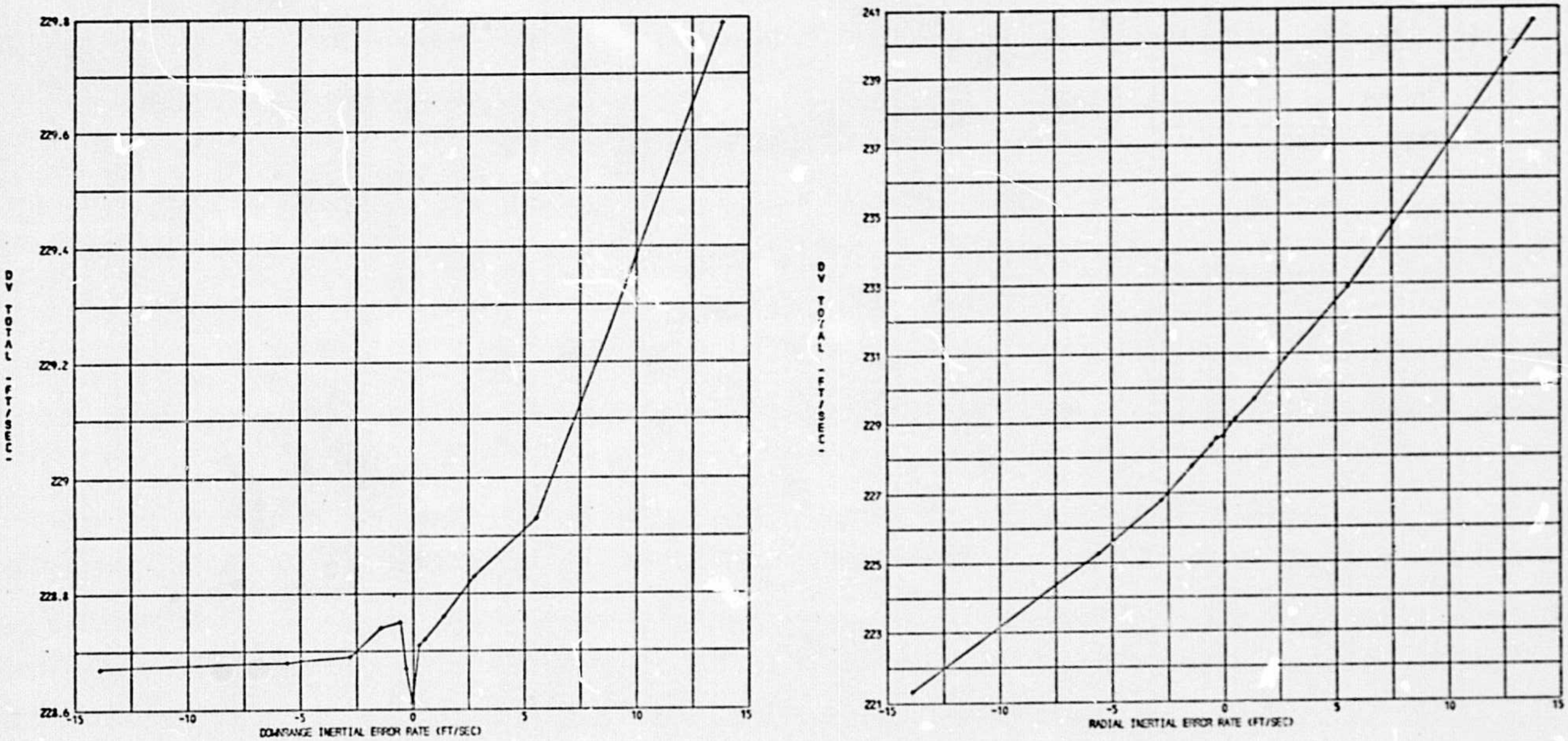


FIGURE 14 - TOTAL DELTA VELOCITY DEPENDENCE ON INERTIAL ERROR RATE

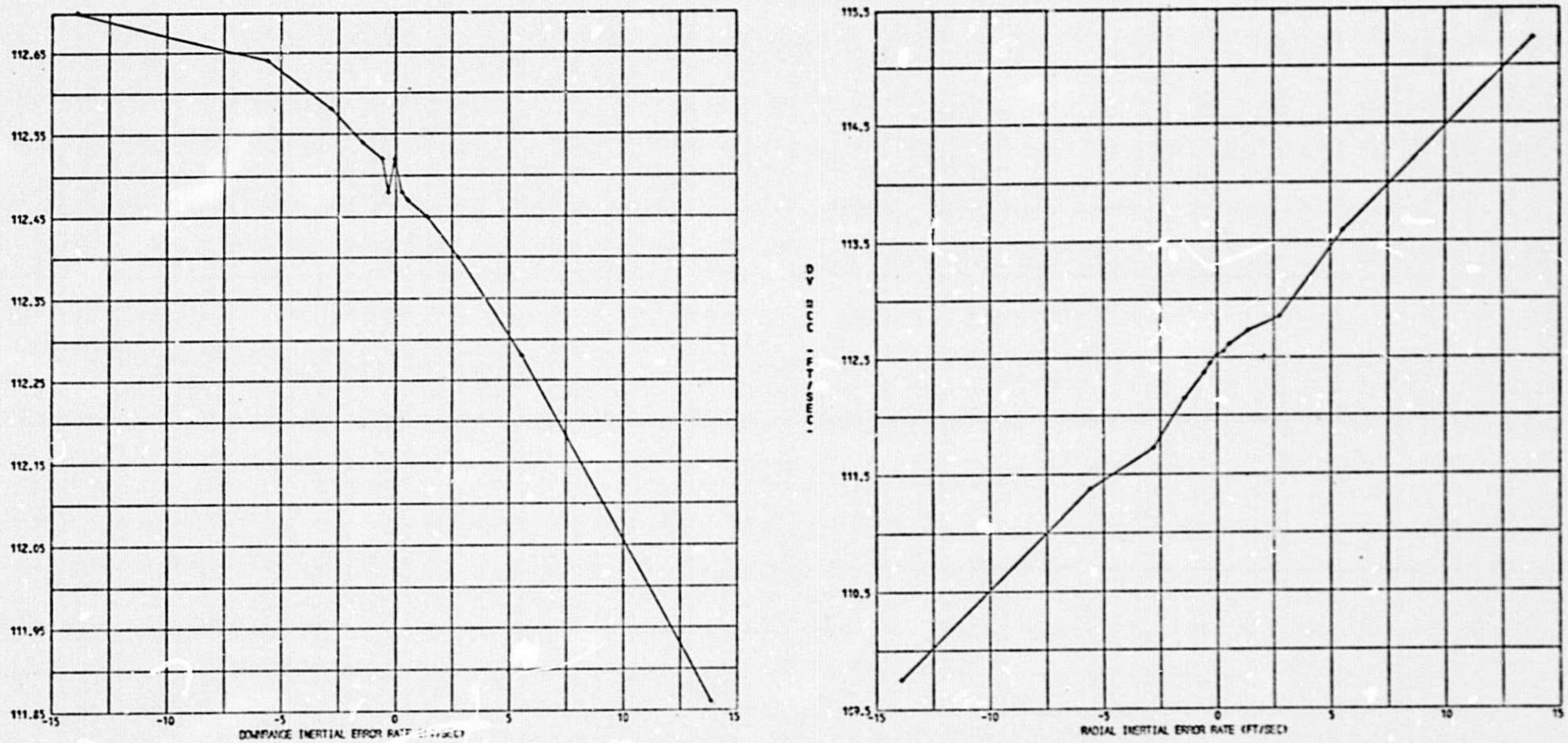


FIGURE 15 - NCC BURN MAGNITUDE DEPENDENCE ON INERTIAL ERROR RATE

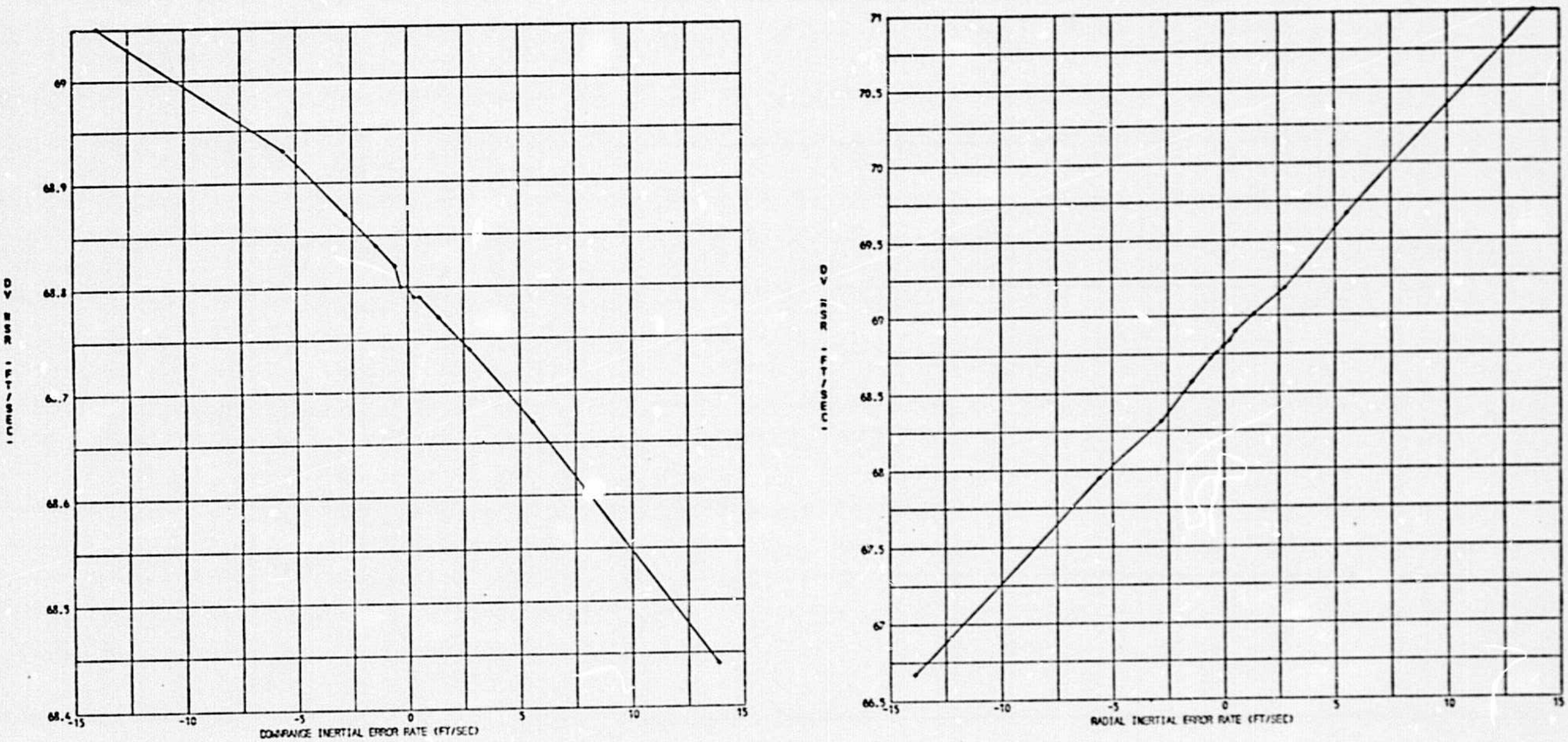


FIGURE 16 - NSR BURN MAGNITUDE DEPENDENCE ON INERTIAL ERROR RATE

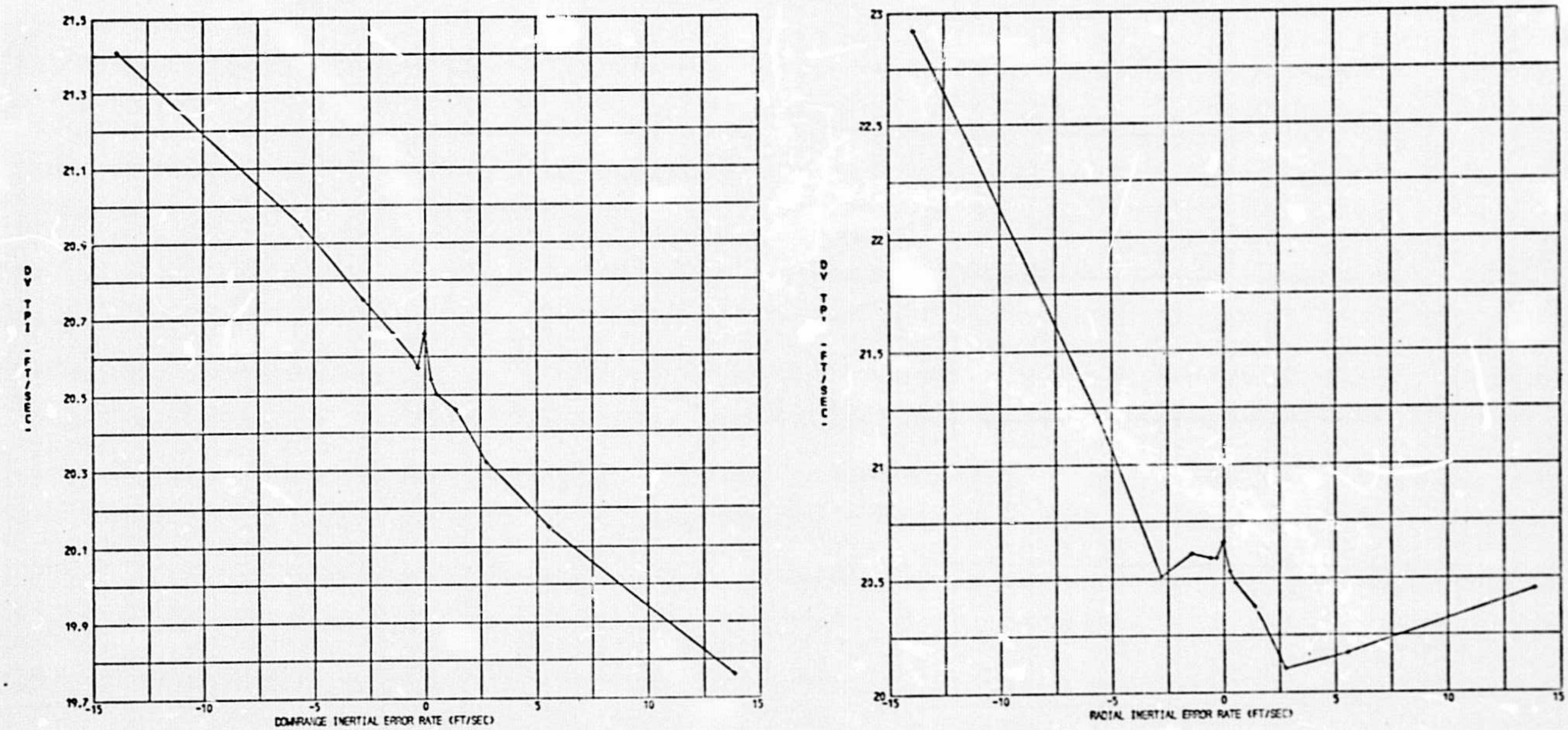
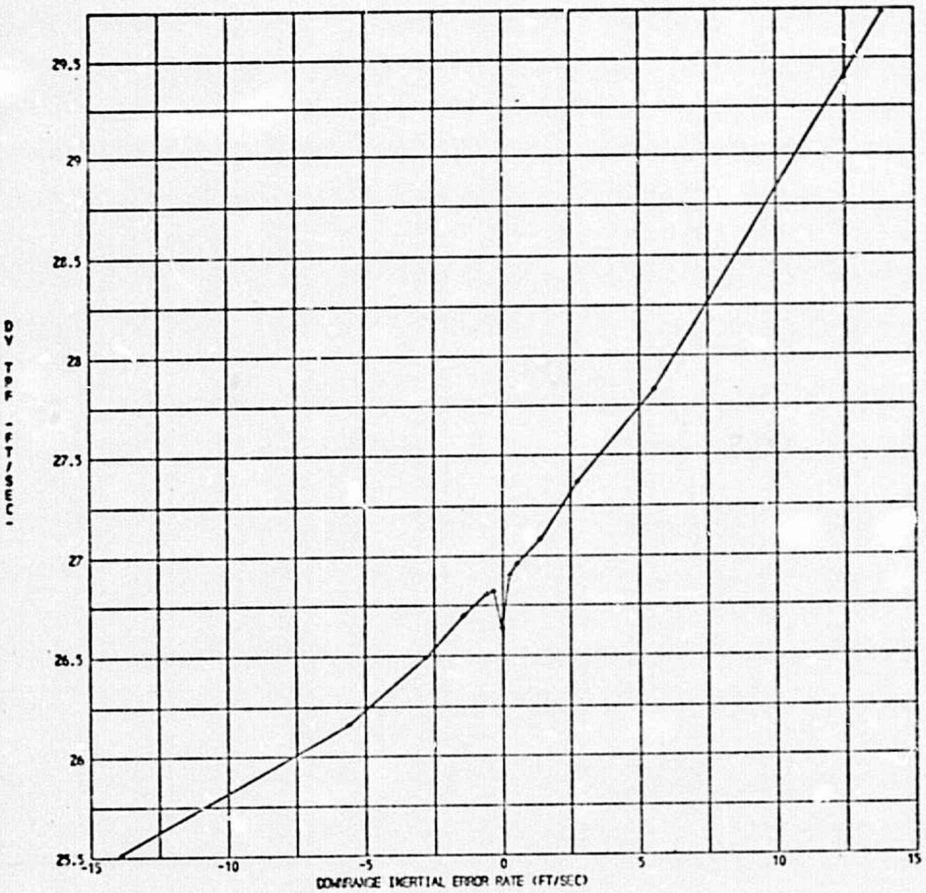


FIGURE 17 - TPI BURN MAGNITUDE DEPENDENCE ON INERTIAL ERROR RATE



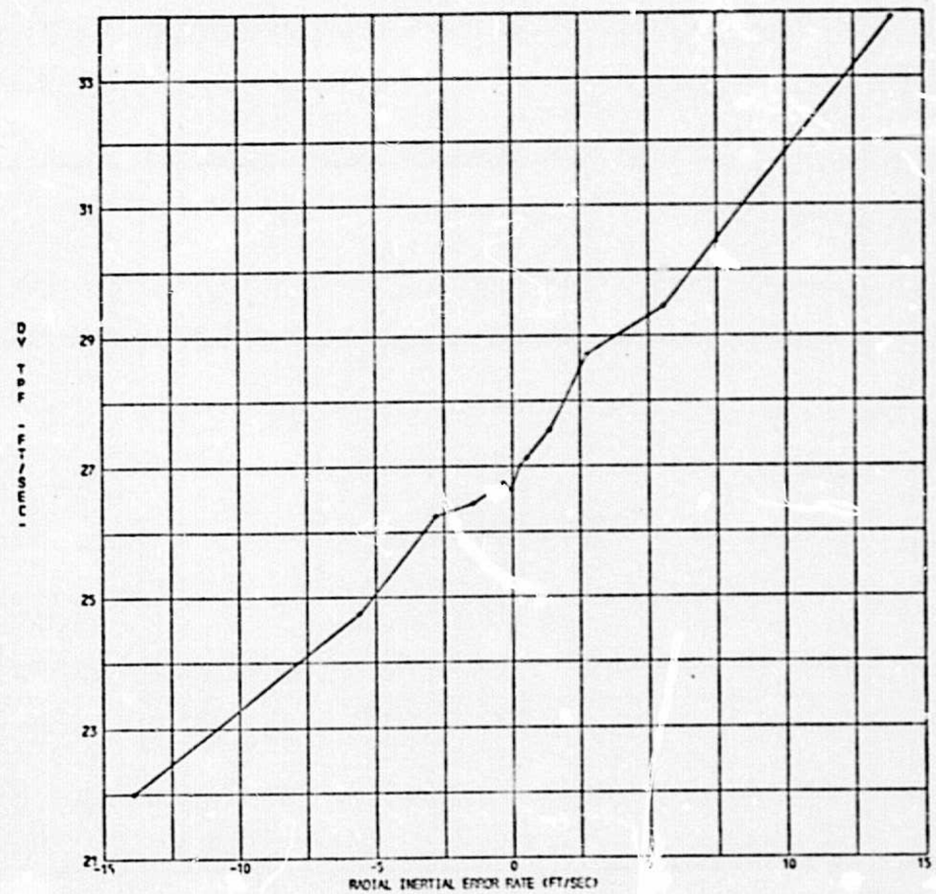


FIGURE 18 - TPF BURN MAGNITUDE DEPENDENCE ON INERTIAL ERROR RATE

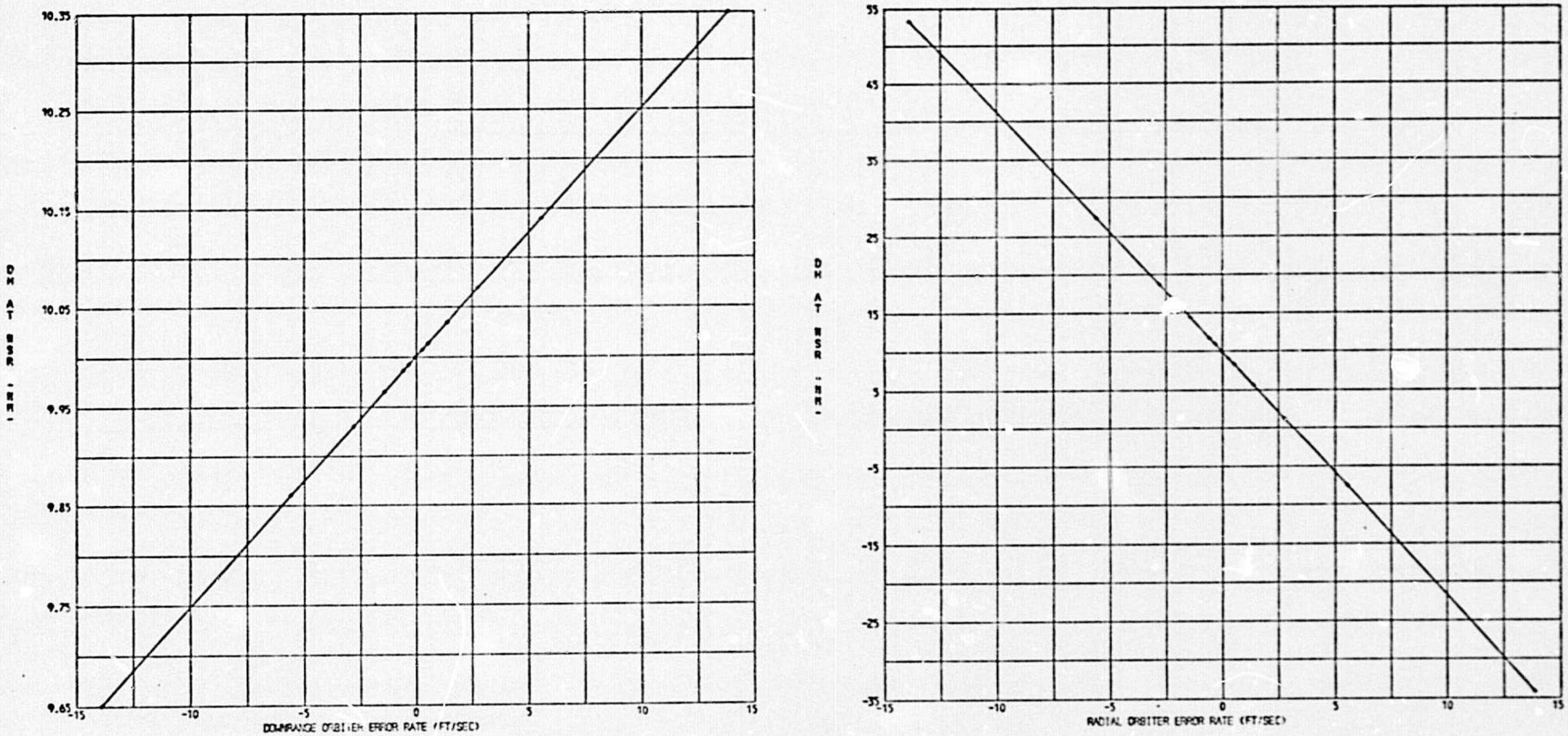


FIGURE 19 - DIFFERENTIAL ALTITUDE AT NSR DEPENDENCE ON RELATIVE ERROR RATE

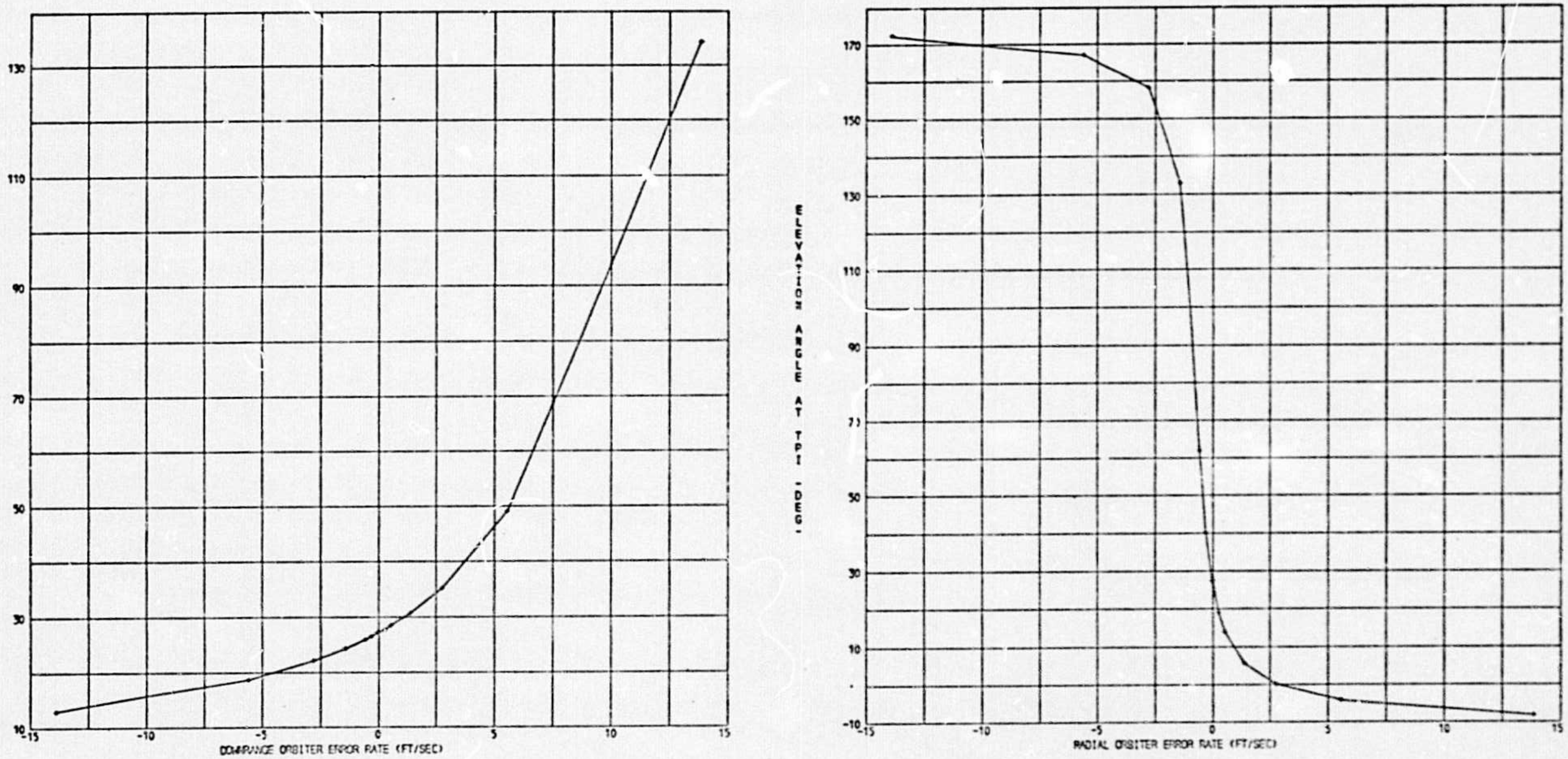


FIGURE 20 - TPI ELEVATION ANGLE DEPENDENCE ON RELATIVE ERROR RATE

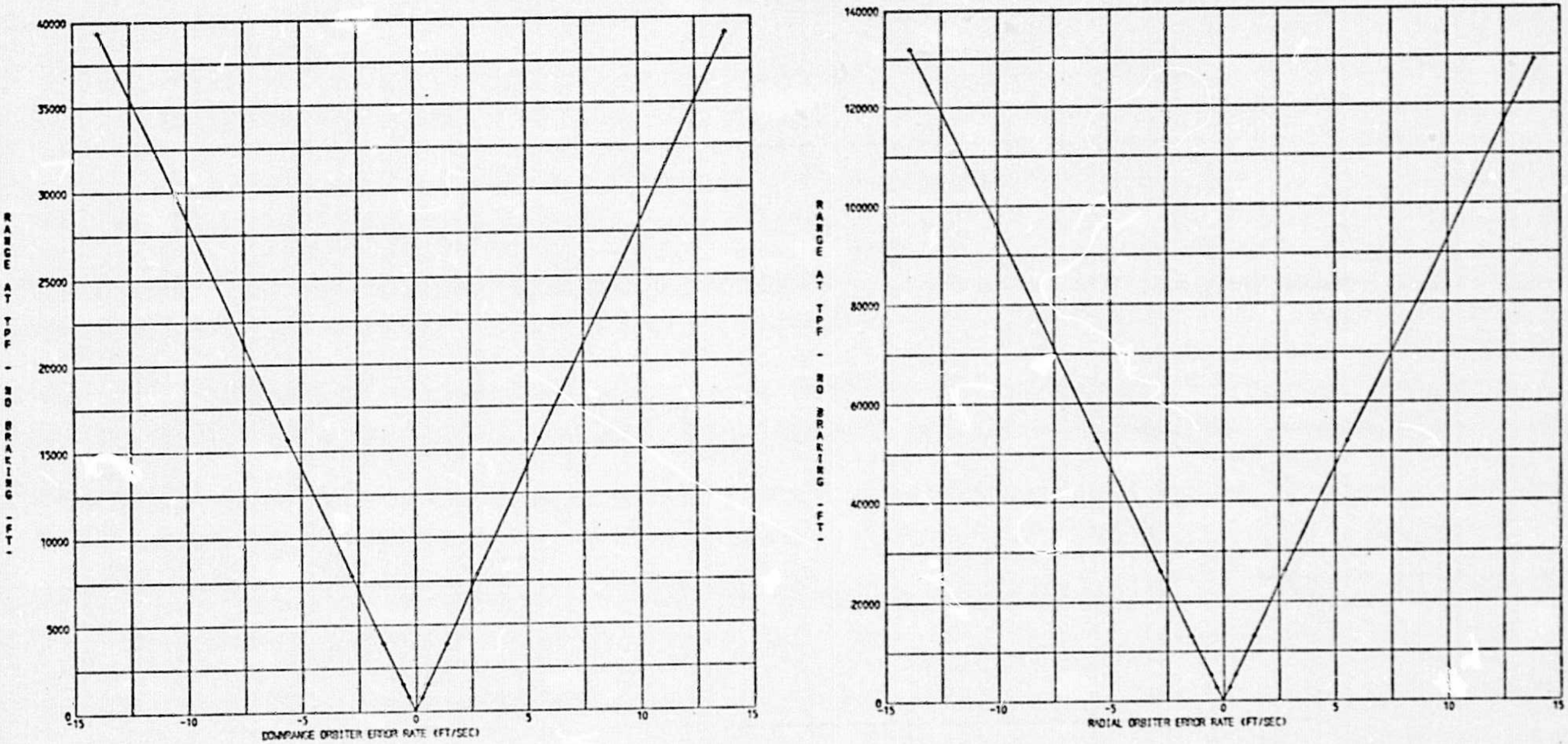


FIGURE 21 - RANGE AT TPF DEPENDENCE ON RELATIVE ERROR RATE

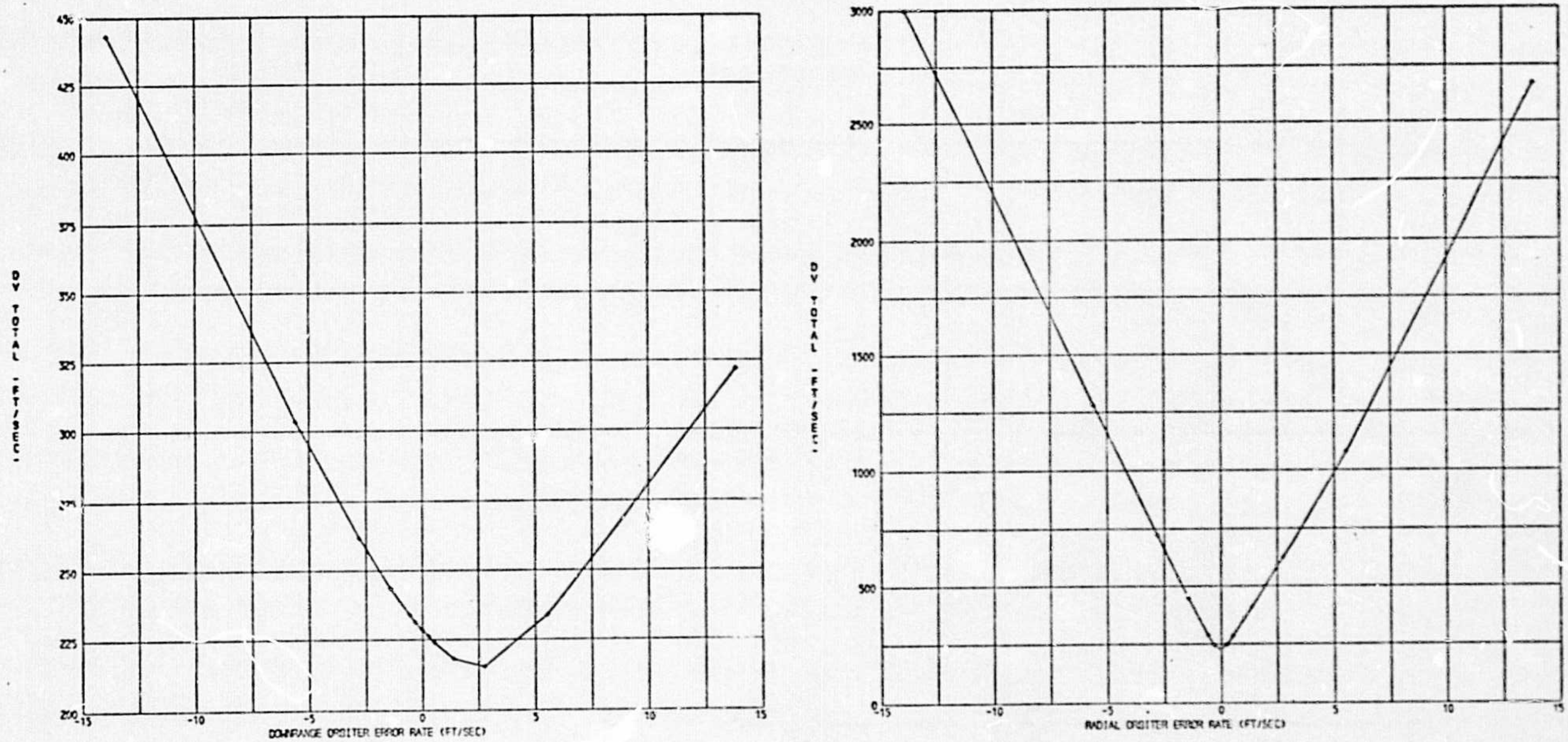


FIGURE 22 - TOTAL DELTA VELOCITY DEPENDENCE ON RELATIVE ERROR RATE

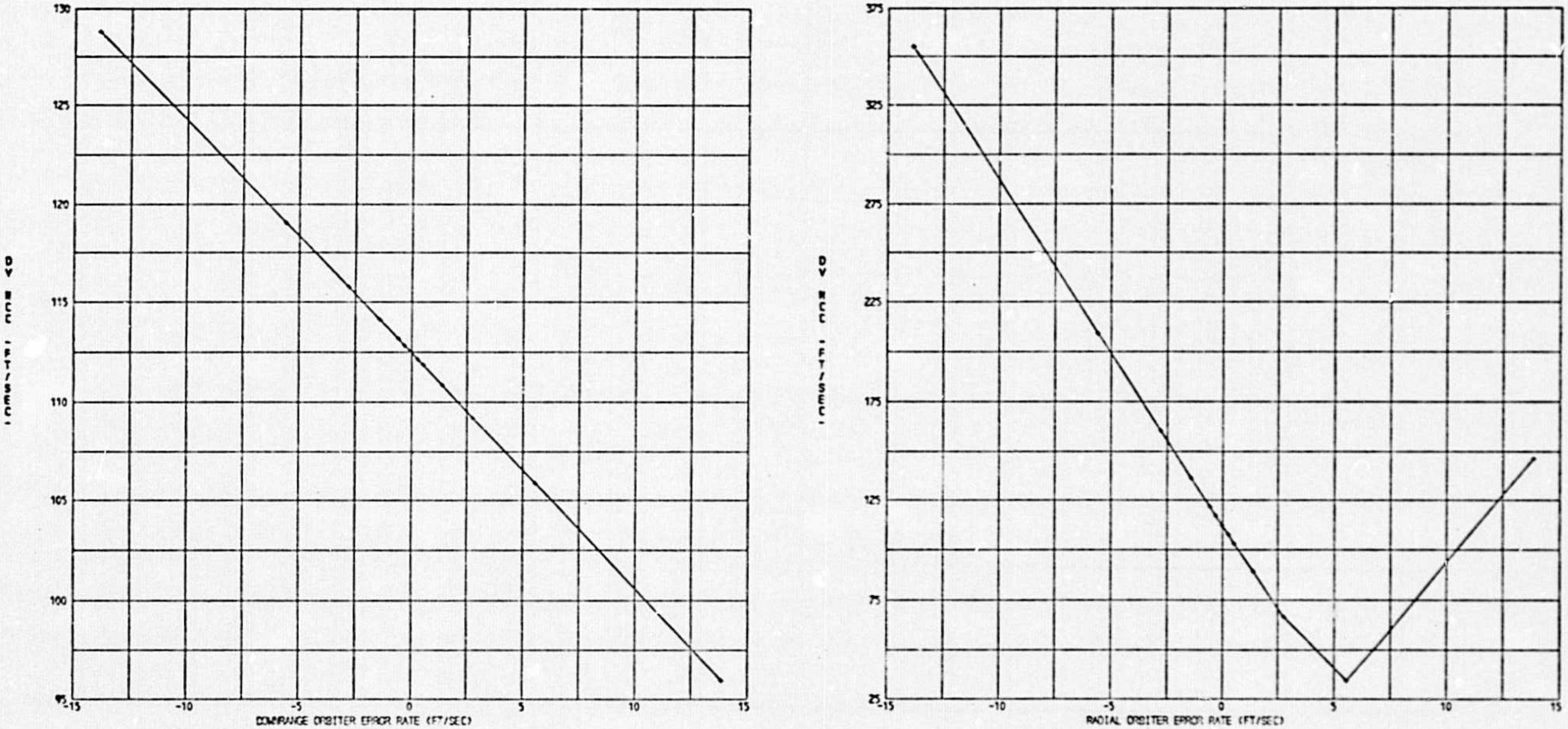


FIGURE 23 - NCC BURN MAGNITUDE DEPENDENCE ON RELATIVE ERROR RATE

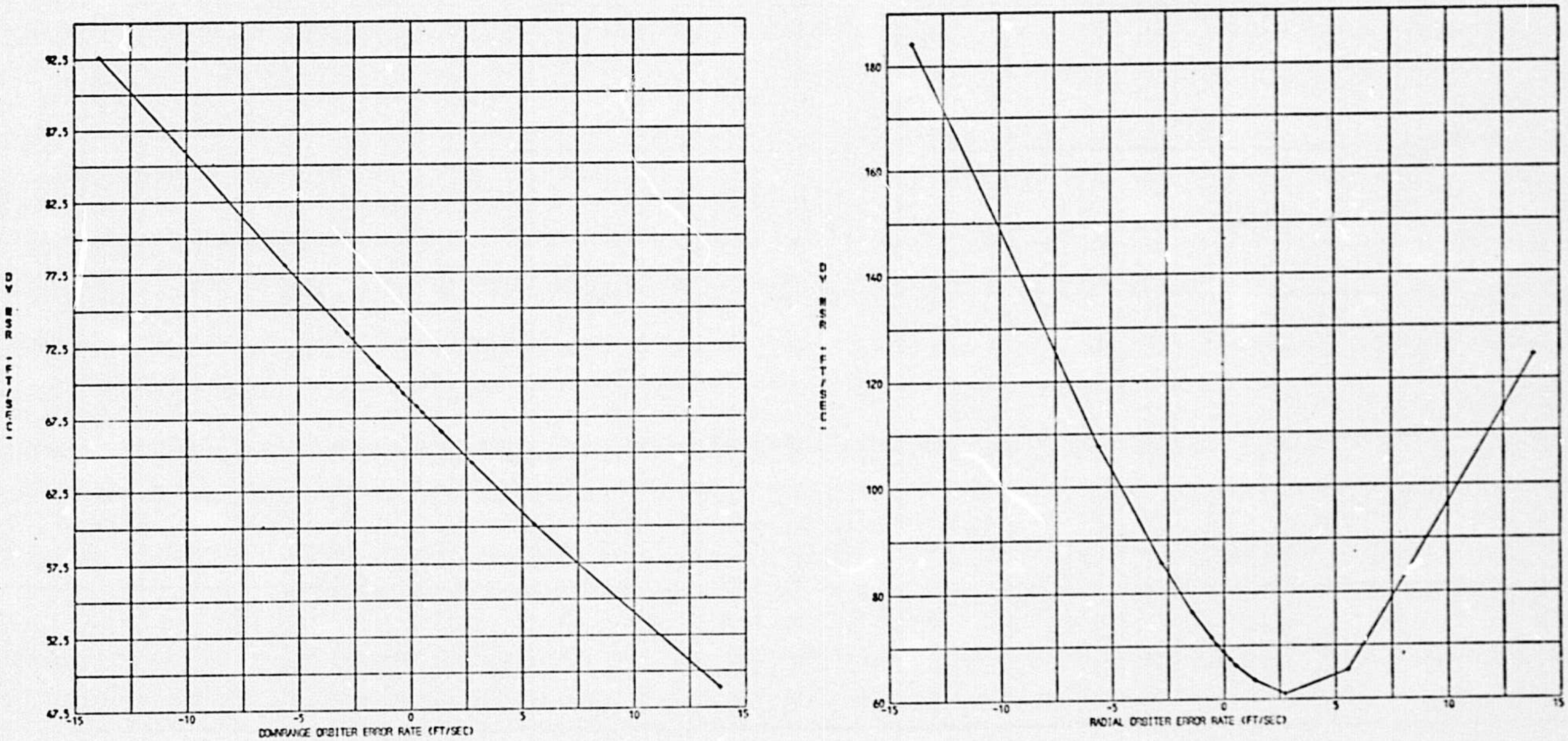


FIGURE 24 - NSR BURN MAGNITUDE DEPENDENCE ON RELATIVE ERROR RATE

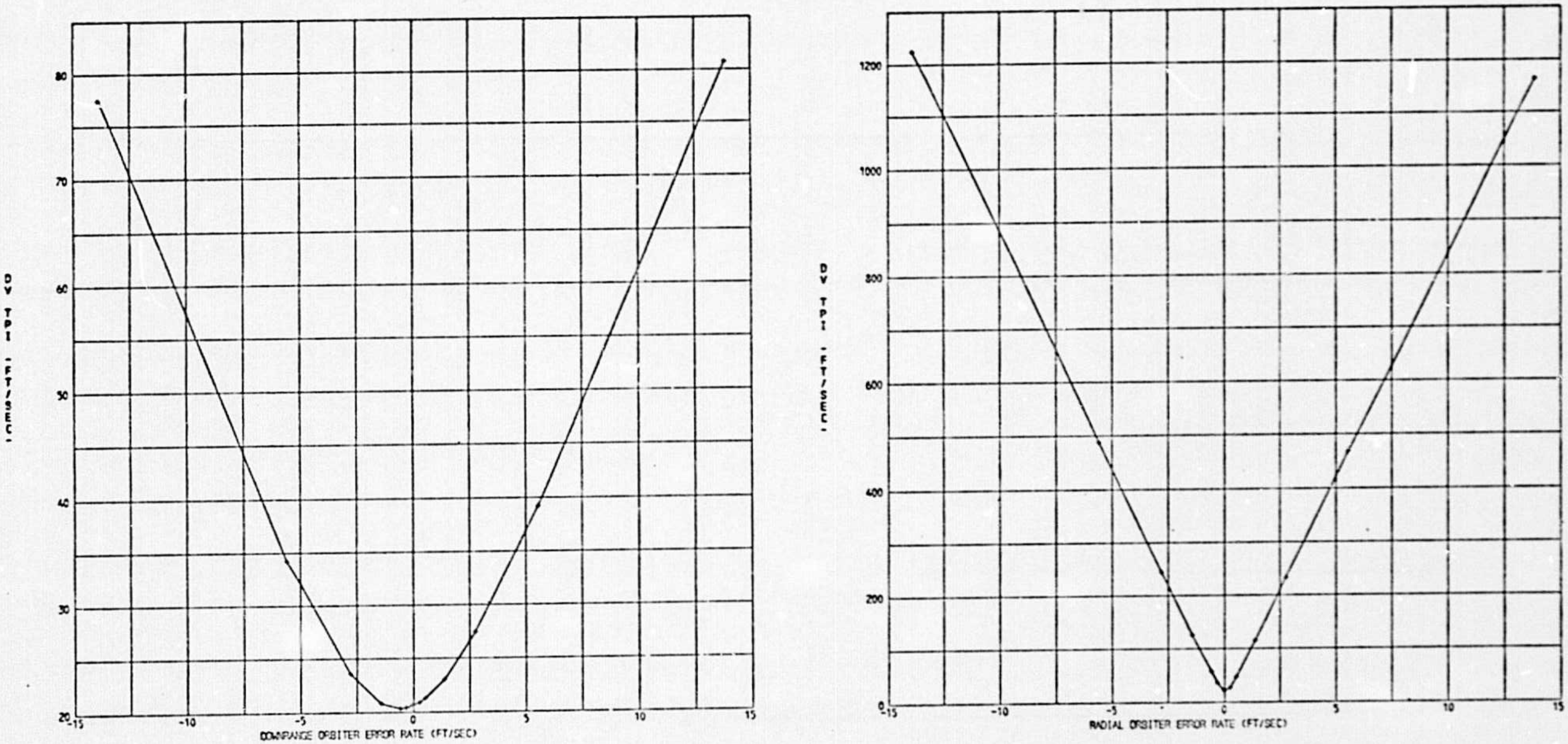
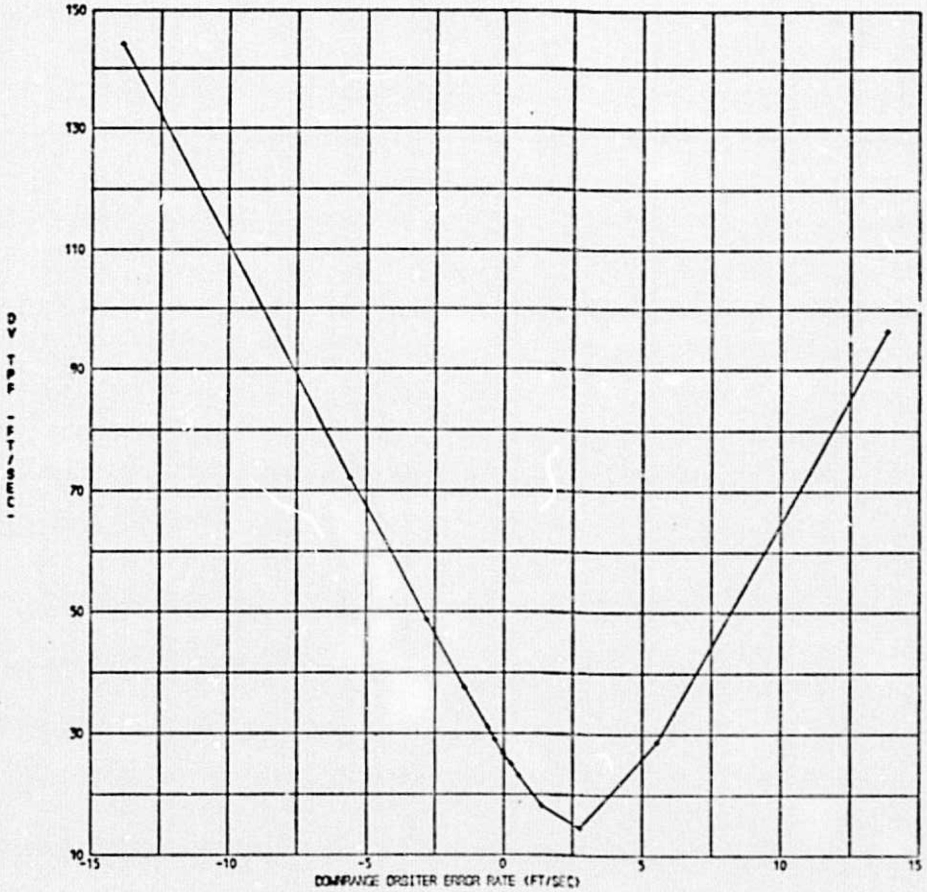


FIGURE 25 - TPI BURN MAGNITUDE DEPENDENCE ON RELATIVE ERROR RATE



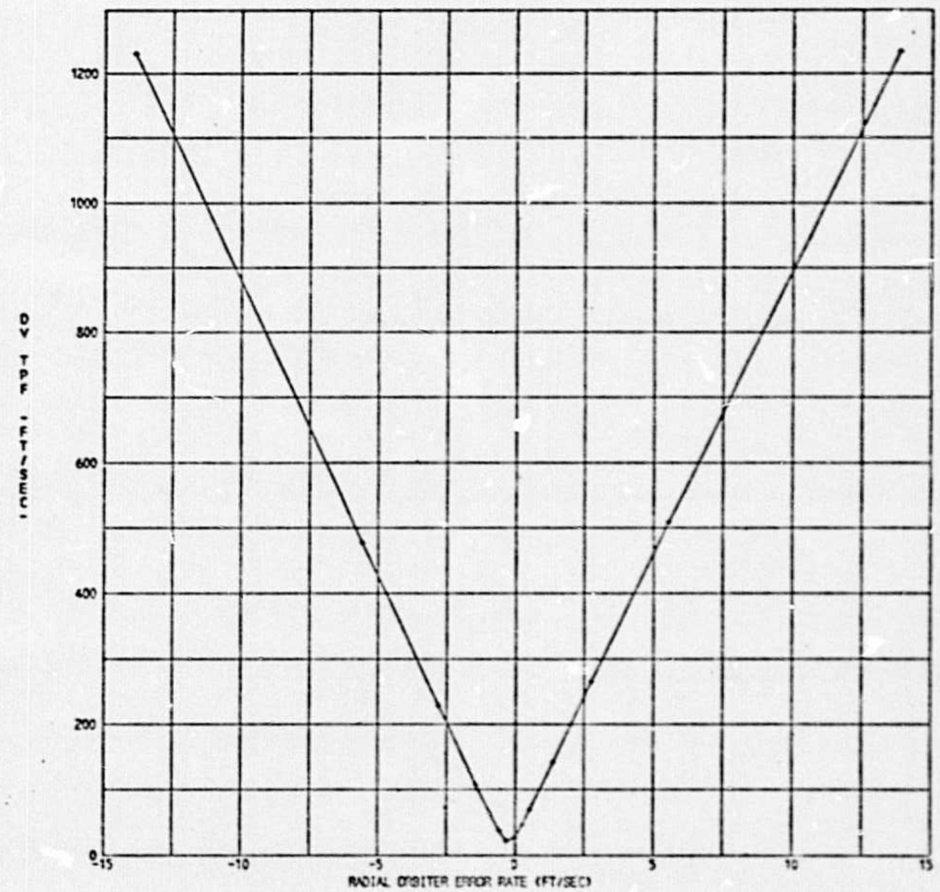


FIGURE 26 - TPF BURN MAGNITUDE DEPENDENCE ON RELATIVE ERROR RATE

5.0 CONCLUSIONS

An examination of the results allow the conclusion that relative errors are more critical than inertial errors and that a radial error rate is more critical than a downrange error rate of the same magnitude. In the inertial case the error in predicting the target state is compensated by a similar error in predicting the orbiter state. The reason that a radial error rate is more important that a downrange error rate is seen by comparing Figures 1 and 2 which indicate that a radial error rate produces much larger curvilinear rotating downrange and radial errors than a downrange error rate.

5.1 Inertial Errors

The main effect of inertial errors is to change the catch-up rate which the targeting logic assumes. If the targeting expects the vehicles to be in a lower orbit than they actually are due to a positive inertial error, it will put the NSR point further out to reach TPI at the proper time. Figure 27 shows the effect of large positive and negative inertial radial error rates on the trajectory. Noting that positive radial error rates produce positive radial (down) errors (Figure 2), the effect of increasing the NSR distance can be seen in Figure 27 and is also indicated in Figure 12 where the elevation angle at TPI is decreasing and in Figure 14 where the ΔV cost of making the larger loop is increasing. The range at TPF (Figure 13) shows the roughly symmetrical effect of missing the target in opposite directions due to the incorrect catch-up rate.

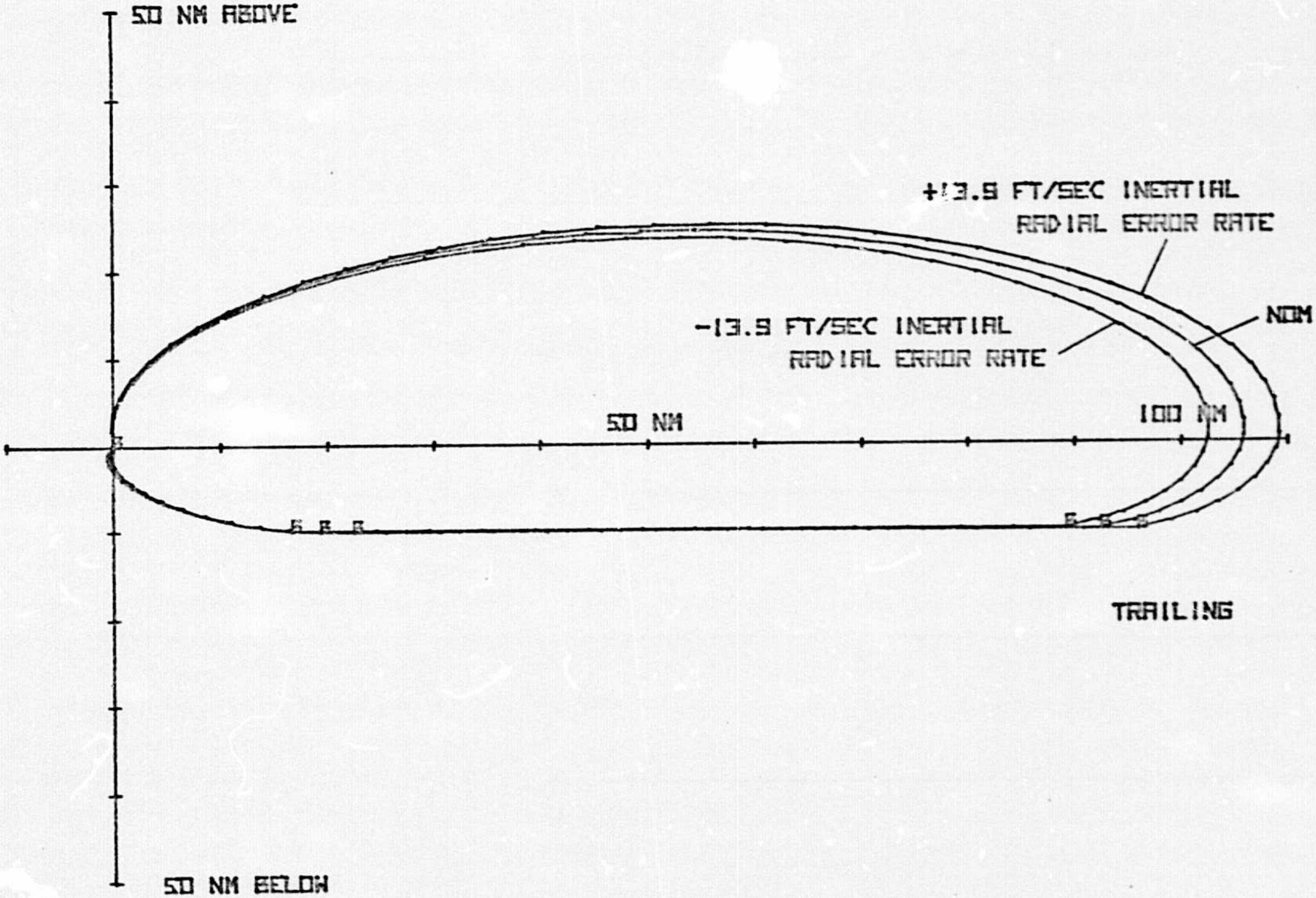


FIGURE 27 - EFFECT OF INERTIAL RADIAL ERROR RATE ON RENDEZVOUS TRAJECTORY

5.2 Relative Errors

A positive downrange error rate produces a negative downrange (behind) error and a negative radial (upward) error (Figure 1). Therefore, the positive downrange error rate results in a smaller relative motion loop than the nominal rendezvous, and a negative downrange error rate results in a larger loop as shown in Figure 28. This deviation from the nominal trajectory explains the results shown in Figures 19 through 26 for the downrange error rate (left side of Figures). Positive downrange error rates result in a lower orbiter trajectory due to the radially upward predictor error as shown in Figure 19, left, by a larger differential altitude at NSR. The increase in elevation angle shown in Figure 20, left, is a result of performing TPI too close and in the case of large error rates performing TPI in front of the target (El > 90°). The range at TPF (Figure 21, left) is symmetrical because error rates of opposite signs produce misses in opposite directions. The total ΔV shown in Figure 22, left, indicates the increased ΔV cost of making much larger or smaller loops.

Positive radial error rates produce positive downrange and radial errors. Therefore, positive radial error rates produce trajectories which tend to be behind and above the nominal trajectory. This is shown in the extreme cases of large radial errors in Figure 29 where the positive error rate produces an NSR burn above the target. The effect of a positive radial error rate is the opposite of a positive downrange error rate (or conversely, the same as a negative downrange error rate) and much larger

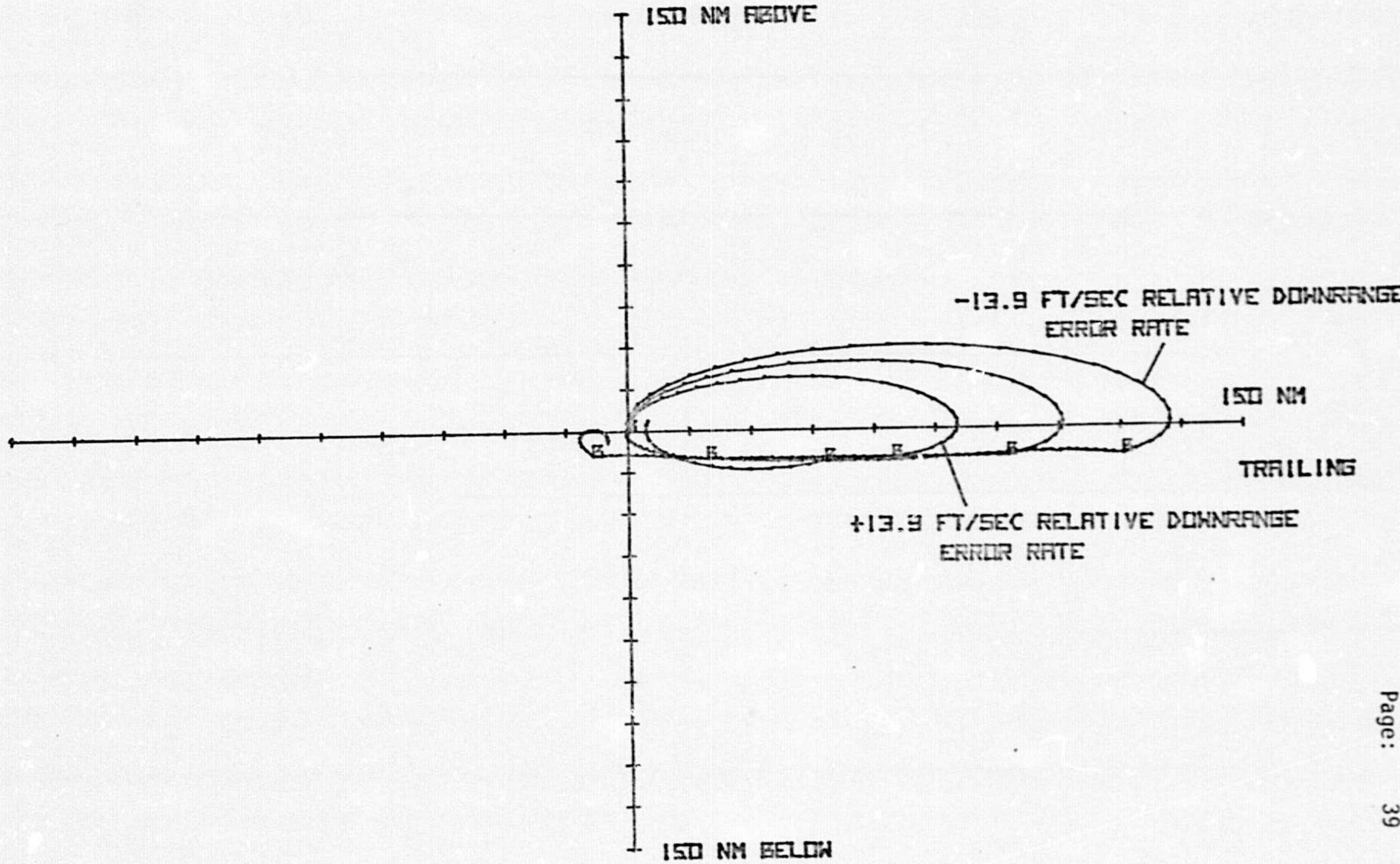


FIGURE 28 - EFFECT OF RELATIVE DOWNRANGE ERROR RATE ON RENDEZVOUS TRAJECTORY

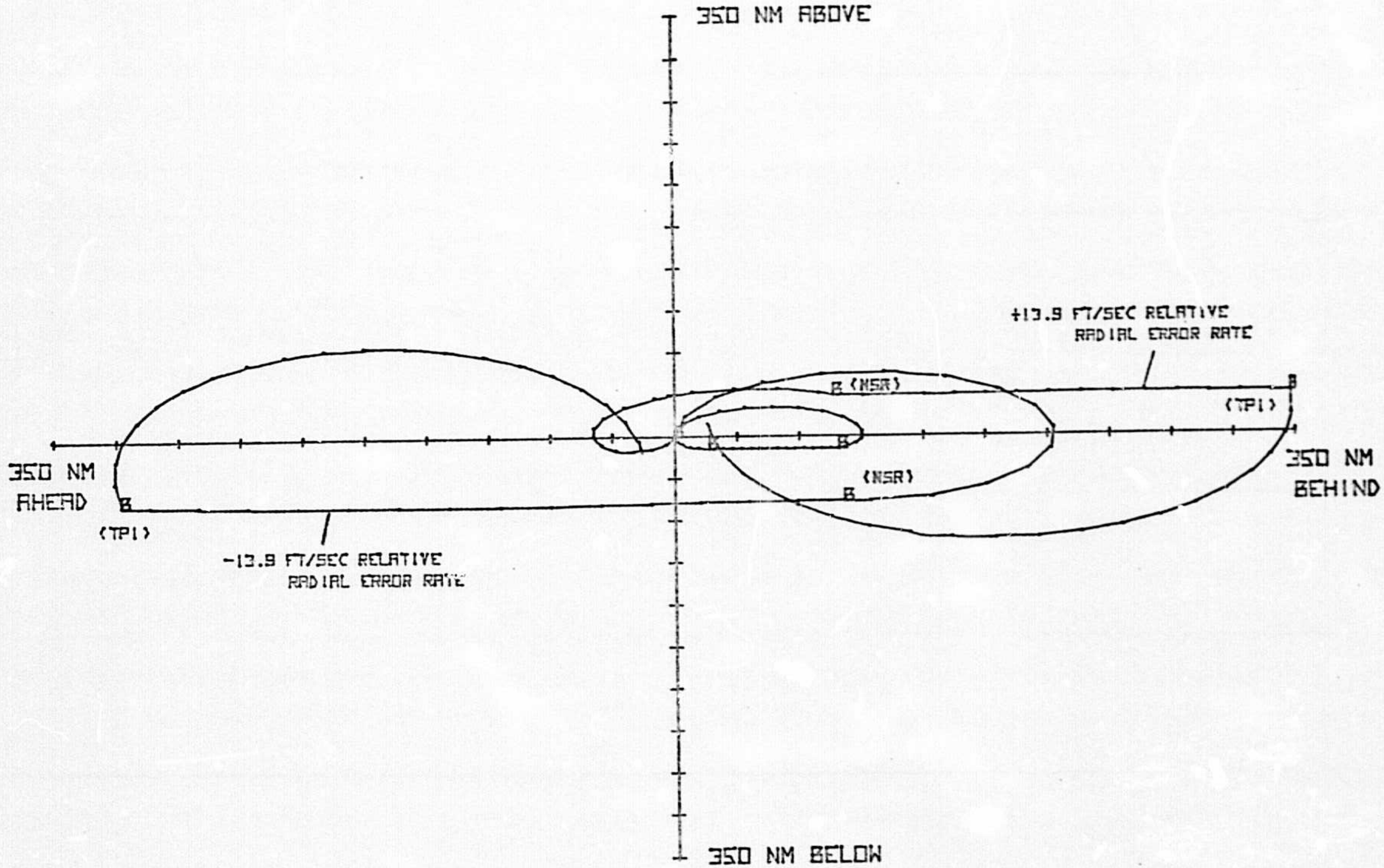


FIGURE 29 - EFFECT OF RELATIVE RADIAL ERROR RATE ON RENDEZVOUS TRAJECTORY

in impact for error rates of the same magnitude. This can be seen in a comparison of the left (downrange error rate) and right (radial error rate) graphs in Figures 19 through 22.

5.3 Sensitivities

The sensitivities in critical parameters based on the results presented in Section 4 are summarized in Figure 30. These represent straight line approximations to the results in the nominal region where the sensitivities are linear as specified in the table. The sensitivities shown in Figure 30 are independent of each other. The total effect of predictor errors on a critical parameter will be the sum of the effects of each error rate (inertial and relative, downrange and radial).

PARAMETER	DIFFERENCE FROM NOMINAL DUE TO ERROR RATE			
	INERTIAL ERROR RATE		RELATIVE ERROR RATE	
	DOWNRANGE	RADIAL	DOWNRANGE	RADIAL
DIFFERENTIAL ALTITUDE AT NSR (DH) NOM: 10 NM	-.01 $\frac{\text{NM}}{\text{FT/SEC ERROR RATE}}$ BETWEEN DH = 9.9 AND 10.1 NM	.01 $\frac{\text{NM}}{\text{FT/SEC ERROR RATE}}$ BETWEEN DH = 9.9 AND 10.1 NM	.02 $\frac{\text{NM}}{\text{FT/SEC ERROR RATE}}$ BETWEEN DH = 9.7 AND 10.2 NM	-3.1 $\frac{\text{NM}}{\text{FT/SEC ERROR RATE}}$ BETWEEN DH = -34 AND +54 NM
ELEVATION ANGLE AT TPI (E) NOM: 27°	-.12 $\frac{\text{DEG}}{\text{FT/SEC ERROR RATE}}$ BETWEEN E = 26° AND 28°	-.22 $\frac{\text{DEG}}{\text{FT/SEC ERROR RATE}}$ BETWEEN E = 24° AND 30°	2.1 $\frac{\text{DEG}}{\text{FT/SEC ERROR RATE}}$ BETWEEN E = 25° AND 31°	-37.8 $\frac{\text{DEG}}{\text{FT/SEC ERROR RATE}}$ BETWEEN E = 22° AND 35°
RANGE AT TPF (R) NOM: 0	12.9 $\frac{\text{FT}}{\text{FT/SEC ERROR RATE}}$ BETWEEN R = 0 AND 180 FT	45.1 $\frac{\text{FT}}{\text{FT/SEC ERROR RATE}}$ BETWEEN R = 0 AND 600 FT	2860 $\frac{\text{FT}}{\text{FT/SEC ERROR RATE}}$ BETWEEN R = 0 AND 40000 FT	9590 $\frac{\text{FT}}{\text{FT/SEC ERROR RATE}}$ BETWEEN R = 0 AND 130000 FT
TOTAL DELTA VELOCITY (DV) NOM: 228.6 FT/SEC	.081 $\frac{\text{FT/SEC}}{\text{FT/SEC ERROR RATE}}$ BETWEEN DV = NOM AND 230 FT/SEC	.704 $\frac{\text{FT/SEC}}{\text{FT/SEC ERROR RATE}}$ BETWEEN DV = NOM AND 241 FT/SEC	11.7 $\frac{\text{FT/SEC}}{\text{FT/SEC ERROR RATE}}$ BETWEEN DV = NOM AND 260 FT/SEC	200 $\frac{\text{FT/SEC}}{\text{FT/SEC ERROR RATE}}$ BETWEEN DV = NOM AND 1000 FT/SEC

FIGURE 30 - LINEAR SENSITIVITIES OF CRITICAL PARAMETERS IN THE NOMINAL REGION